A STUDY OF RAM TYPE INTAKE PARAMETERS

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ABSTRACT

The subject of this paper is an investigation of the significant factors that affect the performance of a sub-cavitating pitot type intake for a waterjet propulsion system for hydrofoil craft. A computer model for design of an inlet nacelle is developed which accepts values of two parameters and several system constants from a control program and designs a nacelle to meet those requirements subject to limitations imposed by cavitation and geometry. The parameters are inlet velocity ratio and inlet diameter to maximum diameter ratio. A body of revolution configuration with profile shape based on certain desirable pressure distributions is assumed. Extensive use is made of empirical data from the available unclassified literature.

The design conditions are those existing at maximum speed, called cruise speed, and the minimum foil-borne speed, called take-off speed.

The subroutine will accept up to three additional speeds at which a performance prediction will be made after design is completed from th first two.

Pressure recovery characteristics and cavitation limits for some typical designs are displayed as graphs.

The subroutine listing and flow diagram is included in Appendix C. In addition, an alternate design method which accepts only the inlet velocity ratio as a parameter is included in Appendix D.

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Figure 21. Cavitation limits as a function of D_i/D_m vs. V_i/V_o at cruise speeds of 40, 45, and 50 knots

LIST OF SYMBOLS

Symbol	Description	Units
A	area in general	ft.^{2}
C	diffuser expansion factor	dimensionless
C_D	Drag coefficient	dimensionless
C_f	Schoenherr friction coefficient	dimensionless
C_p	static pressure coefficient	dimensionless
D	diameter in general	ft.
H	pressure head	ft. of water
K_t	sudden expansion loss factor	dimensionless
L	length in general, also length of the forebody	ft.
P	total or stagnation pressure	pounds/ft.^{2}
Q	flow rate	ft.^{3}/sec.
RPR	ram pressure recovery	dimensionless
V	velocity in general	ft./sec.
W	weight	pounds
X	width of the auxiliary inlet ring normal to the flow	ft.
c_o	strut chord	ft.
f	Moody friction factor for pipe losses	dimensionless
p	static pressure	pounds/ft.^{2}
q	dynamic pressure	pounds/ft.^{2}
t_m	strut thickness	ft.
α	angle of attack	degrees

Symbol	Description	Units
θ	diffuser half angle of expansion, or angle in general	degrees
ρ	density of water	slugs/ft.^{3}
σ	cavitation number	dimensionless
σ_i	incipient cavitation number	dimensionless

Subscript	Meaning
1	refers to conditions at the diffuser inlet or cruise speed
2	refers to conditions at the diffuser exit or take-off speed
o	refers to conditions in the free stream
i	refers to conditions at the inlet or inside
c	refers to the combined flows from the auxiliary and nose inlets
d	refers to the diffuser
m	maximum or mean, depending on context
max	maximum
min	minimum
N	refers to the nacelle
x,Aux	refers to the auxiliary inlet
tv	refers to the turning vanes

Chapter 1.

PROBLEM STATEMENT

Ram (pitot) type inlets for waterjet propulsion systems in hydrofoil craft are responsible for a significant part of both the external drag and internal flow losses and have a strong influence on the propulsive efficiency of the system.

The objective of this investigation is to identify and quantify the significant characteristics of a "well designed" inlet in a manner that will allow their use at the preliminary design stage to assist in rapidly determining the feasibility and relative merit of various propulsion system configurations in a craft of a given size with given speed and range requirements.

The term, "well designed", as used with reference to the inlet and nacelle will mean that inlet configuration which best suits the propulsion system as a whole when optimized with respect to some chosen criterion.

A computer subroutine is to be developed for use with an optimization program concurrently being developed by R. P. Gill (ref. 1) which calls this subroutine and others written by Gill and R. C. Percival (ref. 2). The optimization criterion chosen for this particular program is least propulsion system weight including fuel, but the inlet subroutine, called SUBROUTINE NACEL, does not depend on that particular criterion and could be used for others.

Engineering approximations and empirical fits are

used wherever they are suitable and consistant with the purpose of the study.

There are at least three broad categories of nacelles which could be used for ram inlets: subcavitating, supercavitating, and base-vented. Only subcavitating nacelles are considered in this study. Persons who are interested in supercavitating and base-vented nacelles may wish to read references (3) and (4) for further discussion on those types.

Subsonic aerodynamics provides much of the data utilized in this study, but hydrodynamic design has the additional complication of cavitation avoidance. For the purpose of this paper cavitation is assumed to start when the local static pressure decreases to the vapor pressure of sea water. Incipient cavitation is imposed as an absolute limit on the decrease in static pressure at the design conditions even though a certain amount of cavitation may be allowable in a real life situation.

Chapter 2.

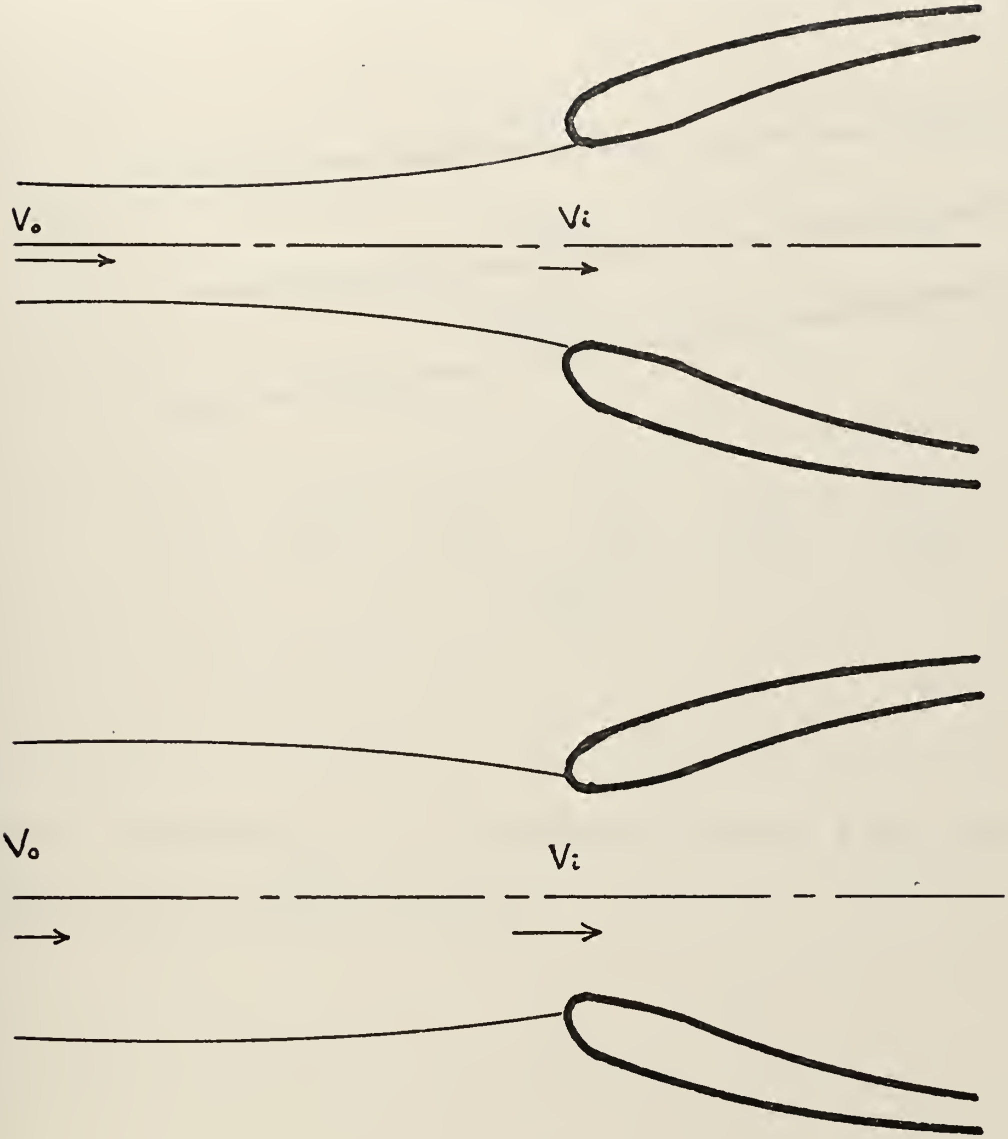
DESIGN CONDITIONS

There are three possible flow conditions at the inlet and Bernoulli's equation indicates the changes in local static pressure coefficient associated with each of them.

When $Vi/Vo < 1$, the stream lines are diverging (Fig.1) and since there are no losses (to the inlet plane, at least), local velocities inside are lower than free stream velocity causing the pressure coefficient to be positive and no cavitation danger exists. Local velocities on the exterior of the forebody are higher than in the free stream and the pressure coefficients are negative (Fig.2), so cavitation danger exists and increases as Vi/Vo decreases. Thus, for any particular nacelle and free stream velocity combination, there is a minimum velocity ratio below which cavitation occurs in the external flow.

When $Vi/Vo > 1$, the stream lines are converging (Fig. 1). Local velocities in the external flow will still be somewhat greater than in the free stream but lower than in the diverging flow case, so if the external flow was cavitation free when $Vi/Vo < 1$, it will also be cavitation free when $Vi/Vo > 1$ at the same Vo. Local velocities in the internal flow are now greater than the free stream with a corresponding decrease in static pressure coefficient, and cavitation inside the lip is a definite possibility. There is therefore a maximum velocity ratio for each nacelle and Vo above which cavitation will occur

$V_i/V_o < 1$



$1 < V_i/V_o$

Figure 1. Entering stream tube illustrating two flow conditions into the nacelle.

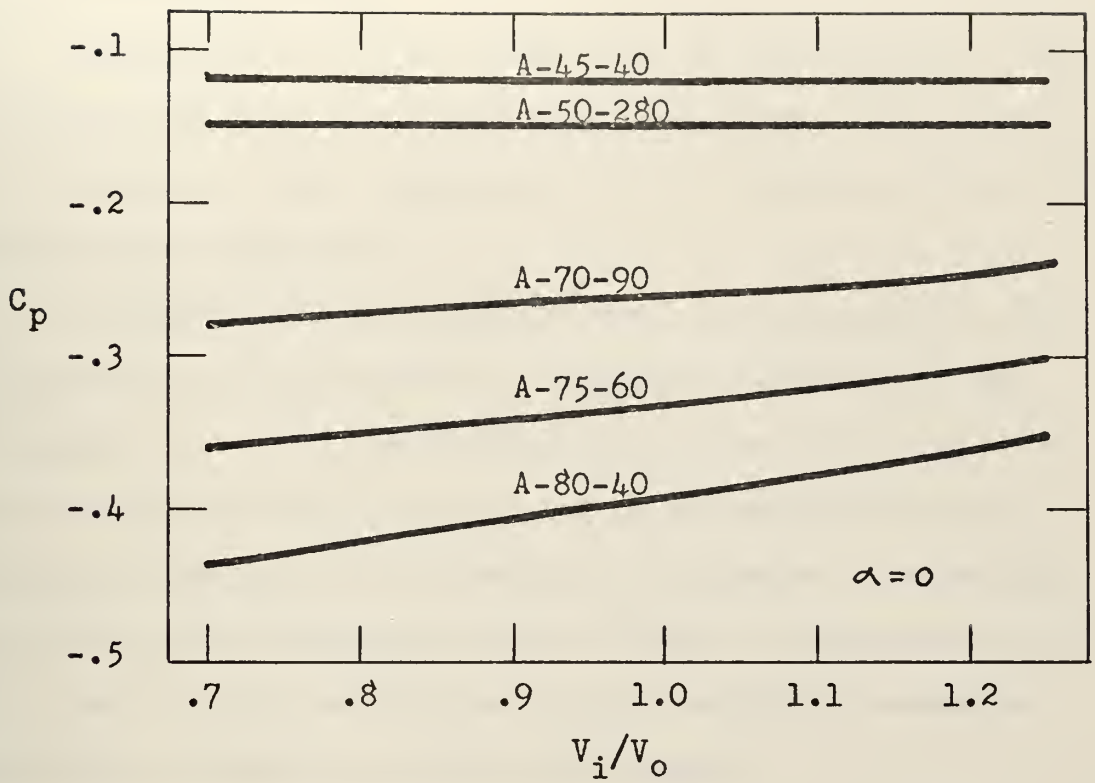


Figure 2. Minimum C_p in the external flow vs. V_i/V_o for several of the Lockheed nacelles

in the internal flow.

When $Vi/Vo = 1$, the flow is in an intermediate state between the other two conditions and no new limitations are imposed. This condition is of no interest, then, from the design viewpoint.

Changes in local velocity due to the geometric configuration of the nacelle, lip shape, bluntness of the forebody, etc., are perturbations on the flow conditions described above and are assumed to be minimized by the detailed design of the nacelle. No attempt is made here to define that detailed design except to assume that it is at least as good as the best of the empirical examples and data available to this investigation.

A very frequently encountered set of requirements, as indicated by the literature, includes the following situation:

Cruise speed is approximately twice take-off speed.

Cruise flow rate is approximately equal to take-off flow rate.

Let the subscripts 1 and 2 designate cruise and take-off conditions, respectively. If the inlet area is a constant,

$$Q_1 = Vi_1\ Ai = Q_2 = Vi_2\ Ai$$

$$Vi_1 = Vi_2$$

but $Vo_1 = Vo_2 \cdot 2$, so $Vi/Vo_1 = \frac{1}{2} Vi/Vo_2$.

If $Vi/Vo_1 = 0.7$ to 0.8 as is frequently the case, (refs. 4,5,6,) then $Vi/Vo_2 = 1.4$ to 1.6, but except when the inlet is very deeply submerged, these high velocity

ratios will cause cavitation inside the inlet, incurring high losses and perhaps choking the inlet.

One way of decreasing this effect is to decrease the inlet velocity ratio at cruise by increasing the area. This approach very quickly reaches the minimum velocity ratio below which cavitation occurs in the external flow with its accompanying high drag and possible material damage.

As speed increases, the interval between these two limits becomes smaller, so the problem grows increasingly difficult as attempts are made to achieve higher speeds.

A solution to the problem may be found in the use of auxiliary inlets to increase the effective inlet area when high velocity ratios are required.

If the existance of an auxiliary inlet is postulated, the velocity ratio at take-off is no longer coupled to the velocity ratio at cruise and both become design conditions as the total inlet area for each must be determined independently.

An additional limitation is imposed by the elbow where the internal flow leaves the nacelle and enters the strut. This elbow will normally contain turning vanes to help minimize losses. Since the local velocities on the turning vane surface will be greater than the average velocity in the flow entering the elbow, a danger of cavitation exists. This turning vane cavitation is avoided by diffusing the flow in the nacelle to reduce the

velocities and increase the static pressure. Therefore, a minimum diffusion ratio dictated by a maximum nacelle exit velocity, above which cavitation occurs in the elbow, is a third design limit. This limit must be checked at both cruise and take-off because it is a function of both the flow rate and the losses.

In summary, then, both cruise and take-off are design conditions and cavitation avoidance establishes absolute limits on the minimum velocity ratio at cruise, the maximum velocity ratios at both cruise and take-off, and the minimum diffusion ratio.

Chapter 3.

NACELLE SHAPE

The principles of design used in jet engine nacelles and air intakes, already established in the field of aerodynamics, can be used for guidance in the selection of waterjet inlet nacelles (ref. 3 and 4).

Küchemann and Weber (ref. 7) have developed the definition of a theoretical optimum nacelle contour by considering the momentum balance between the free stream and the entry plane of a semi-infinite intake. The resultant force on the nacelle is given by

$$F_N = \tfrac{1}{2} \; V_o^2 \, A_i \, (1 - V_i/V_o)^2,$$

but since there can be no resultant force on a semi-infinite body in potential flow, this force must be equal and opposite to the integral of the pressure over the forebody area of the nacelle.

$$F_N = -\tfrac{1}{2}\rho V_o^2 \int_{A_i}^{A_m} C_p \, dA = -\tfrac{1}{2}\rho V_o^2 \int_{A_i}^{A_m} \left[1 - (V_l/V_o)^2 \right] dA$$

If the pressure coefficient is a constant over the entire forebody then the local velocity, V_l, is a constant and the projected frontal area, $A_m - A_i$, required to balance F_N is defined by the above equation. When the local velocity is limited to some maximum value to satisfy Mach number requirements or, in the case of waterjet nacelles, cavitation requirements, then the minimum projected frontal

area and V_{max}. will satisfy the relationship

$$\frac{A_m}{A_i} \geqq 1 + \frac{(1 - V_i/V_o)^2}{(V_{max}/V_o)^2 - 1} \; .$$

The optimum intake contour of Küchemann and Weber is one which at its design V_i/V_o achieves the goal of keeping V_{max} constant and at its specified value over the entire forebody and the equals sign applies.

A_m/A_i can be represented by the square root of its inverse, D_i/D_m, in the case of circular intakes.

$$D_i/D_m \leq \left[1 + \frac{(1 - V_i/V_o)^2}{(V_{max}/V_o)^2 - 1} \right]^{\frac{1}{2}}$$

It can be seen that a maximum value of D_i/D_m is defined by a minimum value of V_i/V_o for any given V_o. One of the design limits chosen in the previous chapter was avoidance of cavitation in the external flow at the relatively low velocity ratio at cruise speed. This can now be translated into a maximum value of D_i/D_m.

It is not practical to build such perfect intakes although intakes with reasonably uniform pressure distributions at certain velocity ratios have been developed (ref. 3, 4, 7). In general, the velocity distribution will have peaks.

The generation of practical contours with acceptiable pressure distributions has been largly a matter of experimental trial and error. Küchemann and Weber describe three sets of geometrically similar shapes which

they designate as Classes A, B, and C. The geometric description of these are given in Table 1 and Figure 3.

References 3 and 4 describe two sets of intakes whose pressure distributions were generated by numerical solutions to the potential flow problem. The Lockheed intakes were chosen for input data for this study chiefly because the data covered a wide range of geometric variation and data on the interal flow distribution was available for each of the individual inlets. The major geometric parameters and peak pressure coefficients for each of the nine inlets is given in Tables 2 through 11. The external contour of these nacelles is very close to, but not quite, elliptical. The internal lip contour is elliptical. The Küchemann and Weber intakes are elliptical both internally and externally. Brown and Traksel state that this variation has an influence that is secondary to the length to diameter ratio, L/D_m, and D_i/D_m. Figure 4 shows the similarity of the major parameters. The dashed line was tabulated as the basic geometric description of nacelle forebodies for SUBROUTINE NACEL. The three data points to the left represent intakes which had lower pressure coefficients than the others, so the dashed line represents the best of the available data points.

To obtain a functional relationship for the variation of pressure coefficient with geometery, the peak pressure coefficient at each velocity ratio and at each angle of

attack was plotted against the value of D_i/D_m and also against L/D_m. L/D_m was chosen as the appropriate parameter to use because it gave a smoother distribution of data points. The desired relationship was then obtained by drawing a smooth envelope that enclosed all points and passed through the points of highest C_p. This envelope is considered to represent the "well designed" inlet mentioned in the problem statement based on the assumption that if a nacelle has already been designed which falls on that line (the discrete data points through which the line was drawn), then a nacelle could be designed for any other point on that line. The plots are shown in Figures 5 through 10. Figures 11 through 16 show similar plots for the internal flow conditions.

There can be no losses in the stream tube from out in the free stream up to the inlet plane, but from the inlet plane on into the ducting of the nacelle friction and turbulence take a toll of the head available in the internal flow. The amount of head loss is primarily a function of velocity ratio, Reynolds number and lip shape. Blackaby and Watson investigated experimentally several lip shapes including circular profiles, elliptical profiles and sharp profiles. In general, the elliptical profile caused less losses at a given V_i/V_o than the others. The particular results for the lip which they designated 18E is given as a function of Reynolds number for several velocity ratios in reference 3, Figure 74 of Report No. 5. The loss

coefficient, defined as $\Delta P/q_o$, approaches a constant value for each velocity ratio for Reynolds numbers greater than $8x10^4$. These constant values as read from the citation above are given in Table 12. The Ram Pressure Recovery, defined as

$$RPR = (P - p_o)/(P_o - p_o) = 1 - \Delta P/q_o$$

is plotted in Figure 17, and points from that plot are tabulated in the subroutine.

Chapter 4

THE DIFFUSER

The inlet nacelle modeled in this study is assumed to consist of a streamlined body of revolution containing a nose intake opening, a diffuser and an auxiliary inlet. The forebody and intake lip serve to guide the flow into the internal ducting. That internal ducting includes the diffuser which has at least two primary functions. One is to slow the flow velocity to below the critical value for cavitation in the strut elbow. The other is to decrease the flow velocity further to reduce ducting losses if it benefits the system as a whole.

Three main profile shapes of diffusers with circular cross section can be considered. They are bell, trumpet and straight walled conical diffusers. To avoid confusion of terms, a bell diffuser is one having its mean diameter greater than the mean diameter of a straight walled conical diffuser with the same inlet and exit areas while a trumpet diffuser has a mean diameter less than that of the cone. At similar inlet flow conditions, the bell shape results in a lower total head loss than the other two and the trumpet results in a higher loss (ref. 4, 9).

In general, the diffuser with the least loss in total head is preferred for this application if other considerations are equal because the difference in losses must eventually be made up by expenditure of prime mover power.

Current knowledge of boundary layer growth and behavior in adverse pressure gradients does not allow accurate prediction of diffuser performance by analytic methods (ref. 3), and very little empirical data on bell diffuser performance that is directly applicable was found. Reference 9 contains an experimental comparison of the three shapes which indicates that conical diffusers have pressure recovery characteristics very close to the bell and significantly better than the trumpet. Experimental results contained in references 9 through 13 can be applied to predict the losses of straight walled conical diffusers and can be considered a lower bound of that which can be expected from a bell.

The total pressure loss for a conical diffuser can be predicted by

$$\Delta P = (C\ K_t + f\ L/d_m)\ q_1, \quad \text{(ref. 13)},$$

where the second term is a ducting loss of a duct the same length as the diffuser and of a diameter equal to the mean diameter of the diffuser. For a cone,

$$d_m = (D_1 + D_2)/2 \quad .$$

The first term accounts for diffusion losses as a percentage of the losses in a sudden expansion. K_t is the sudden expansion loss factor and is given by

$$K_t = (1 - A_1/A_2)^2 \quad .$$

The proportionality factor C is a function of ex-

pansion angle, θ, or the double angle, 2θ, and is determined experimentally as in reference 13.

The minimum loss for any given diffusion ratio occurs when the value of 2θ is in the vicinity of 5° to 10°. Flow separation starts interfering with the flow and partially stalling the exit when 2θ is in the vicinity of 20° (ref. 11), therefore the region of interest is for 2θ less than 20°. In this region the curve of C vs. 2θ can be approximated by

$$C = 3.190 \times 10^{-3} (\theta)^2 + 8.452 \times 10^{-4} (\theta)$$

where θ is in degrees.

There appears to be no reason in this application to decrease the angle below the value of minimum loss because the diffuser length increases and friction losses start to rise accordingly. For the computer model limits of 3° and 10° were set on the minimum and maximum values of θ which has the effect of establishing a maximum and minimum length.

The desired total length of the nacelle is generally established by external hydrodynamic flow, structural and other considerations that do not include the diffuser and other internal length requirements. If the internal component lengths are less than the desired length, they will all fit within the envelope. If not, additional external drag due to the added length and wetted surface is generated and the power required to overcome that drag increment can be charged to the diffuser length since other internal

lengths are fixed. This becomes a criterion for determining the proper diffuser length. The sum of the power required to overcome diffuser losses and the additional power due to the increment in drag is minimized with respect to diffuser length. The calculations used in this determination are given in Appendix B.

A limit on the minimum diffusion ratio is given by the requirement that the maximum diffuser exit velocity must be less than the critical velocity which will cause cavitation in the elbow. Experimental results in reference 11 give exit velocity profiles for six diffuser examples, in two of which $2\theta = 10^{\circ}$ and in four of which $2\theta = 12^{\circ}$. The diffuser area ratio was 2.0 in all cases, entry Mach number was 0.26, and boundary layer thickness ranged from 0.003 to 0.03 times the entry radius. Integration of these distributions graphically gives a range of $V_{max.}/V_{ave.} = 1.15$ to 1.50, with a mean value of 1.33 over the six cases. However, since boundary layer thickness has poor predictability, the average exit velocity is not known but it will be somewhat greater than the flow rate divided by the exit area. If $V_{max.}$ is calculated by

$$V_{max.} = k\ Q/A_2,$$

k = 1.33 will probably give a low value and k = 1.50 may give a high value but will be on the safe side.

The upper limit on $V_{max.}$ will be the critical value of V_2 determined from Appendix A.

Chapter 5.

THE AUXILIARY INLET

It was indicated in chapter 2 that an auxiliary inlet was probably required to obtain the flow rates necessary at take-off speed and remain subcavitating at cruise.

The possible configurations for providing auxiliary inlets are many and varied. Slots in the nacelle wall with doors that open inward, leading edge openings on the strut and a movable nacelle lip are all possibilities, to mention only a few.

The model for this study was assumed to be of the first type. Figure 3 shows the auxiliary inlet as dashed lines in the profile. It is assumed that the inlet is in the form of a series of openings in an annular ring around the nose opening with some fraction of that ring being structure to support the nose. The dimension X in the figure is the width of that annular ring in the direction normal to the inlet flow through the opening.

The auxiliary inlet flow is assumed to enter and combine with the flow from the nose opening prior to entering the diffuser because that is the area of lowest static pressure and, since the inlet will only be used at take-off when the flow rate is high, it is important that the entire combined flow pass through the diffuser to prevent cavitation in the elbow.

When the inlet is closed the length of ducting, L_x,

associated with it is considered to be a short length of pipe and the loss for that length of pipe is added to the other system losses.

This type of inlet appears to be in much the same flow conditions as the "gliding scoop" described in reference 14. Since the auxiliary inlet is open only when the system demands a high flow rate its inlet velocity ratio is estimated to be about 1.0 or slightly higher. In this condition the lip loss coefficient is approximately 0.2 (ref. 14). This value is the one used in the subroutine for auxiliary inlet losses.

Chapter 6.

DESIGN RATIONALE

The design of an inlet for the specific conditions imposed by the optimization program is based on comparison of the characteristics implied by the system parameter values with those stored in the data tables and sizing the individual components to remain cavitation free at the design conditions. The subroutine listing and a computer generated flow diagram are in Appendix C. This and the following chapter will attempt to clarify the reasoning used in its derivation.

When the program calls SUBROUTINE NACEL, all physical constants, craft configuration, depth of submergence, free stream velocity, flow rate and angle of attack for each design point are known. Inlet velocity at cruise and D_i/D_m are passed as system parameters. Actually, V_i/V_o at cruise is the system parameter, but it is calculated from V_i and V_o rather than passed.

Initially, free stream static pressure, free stream dynamic pressure, incipient cavitation number, and total pressure for both cruise and take-off speeds are calculated.

$$q_o = \tfrac{1}{2}\rho V_o$$

$$\sigma_{oi} = (p_o - p_v)\tfrac{1}{2}\rho V_o^2$$

$$P_o = p_o + q_o$$

The length to diameter ratio, L/D_m, of the nacelle for

which the external minimum pressure coefficient is equal to the negative of the free stream incipient cavitation number at cruise is determined by interpolation in the data table where

$$L/D_m = f(C_p, V_i/V_o, \alpha).$$

The inlet to maximum diameter ratio, D_i/D_m, corresponding to that L/D_m is found in the tabulated geometric characteristics. The value obtained defines a nacelle for which the external flow on the surface is at the point of incipient cavitation and therefore is a maximum value.

$$(D_i/D_m)_{max} = f(L/D_m)$$

If the D_i/D_m passed by the calling program is greater than $(D_i/D_m)_{max}$, that particular set of parameters is rejected by setting the nacelle weight to a very high number and returning to the calling program. If D_i/D_m is less than $(D_i/D_m)_{max}$, then it is cavitation free and the design proceeds.

Inlet area is determined from the flow rate and inlet velocity at cruise which then allows D_i and D_m to be determined.

The maximum allowed velocity ratio for both speeds is determined by interpolation in the data table again.

$$(V_i/V_o)_{max} = f(L/D_m, \sigma_{oi}, \alpha)$$

This limit is imposed by cavitation on the inside of the lip.

If at cruise, V_i/V_o is greater than $(V_i/V_o)_{max}$, the parameters are rejected in the same manner as before. If

not, the take-off condition is checked to determine if an auxiliary inlet is required. The maximum flow rate allowed by $(V_i/V_o)_{max}$ enters through the nose inlet, the remainder must enter through the auxiliary inlet.

The pressure recovery of the lip is a tabulated function of V_i/V_o, so the total pressure inside the inlet is

$$P_i = RPR_{lip}\, q_o + p_o$$

and the static pressure inside is given by

$$p_i = P_i - \tfrac{1}{2}\rho V_i^2 \ .$$

Pressure recovery of the auxiliary inlet is known from chapter 5 so the total pressure inside the auxiliary inlet is

$$P_{aux} = RPR_{aux}\, q_o + p_o \ .$$

The static pressure at a point is unique so the static pressure inside the auxiliary inlet is the same as that previously calculated from the flow inside the nose inlet. Therefore, the velocity through the auxiliary inlet is

$$V_{aux} = \left[2(P_{aux} - p_i)/\rho\right]^{\frac{1}{2}} \ .$$

The area of the auxiliary inlet is found by

$$A_{aux} = Q_{aux}/\, V_{aux} \ .$$

The total pressure of the combined flow is estimated as the mass weighted average of the combining flows.

$$P_c = (Q_{aux}\, P_{aux} + Q_i\, P_i)/\, Q_c$$

where $$Q_c = Q_{aux} + Q_i \ .$$

The average velocity of the combined flow is

calculated from the dynamic pressure

$$V_i = \left[2(P_c - p_i)/\rho \right]^{\frac{1}{2}} ,$$

and the pressure recovery coefficient to this point is

$$RPR_c = (P_c - p_o)/ q_o .$$

The diffuser entry and exit diameters are set by

$$D_1 = D_i , \; D_2 = 0.9 \; D_m .$$

The 0.9 factor is somewhat arbitrary. Some fraction of the nacelle diameter must be allowed for structural requirements and it was felt that ten per cent would be sufficient in most cases.

The internal component length requirements are calculated in the manner of Appendix B and the sum of those lengths plus the lip length is used as the nacelle length subject to a minimum value of 5.5 D_m. This factor is also arbitrary and is the average of the recommended values of L_N/D_m found in the literature. Hoerner (ref. 15) shows from empirical data that the minimum drag nacelle on a wing has a L_N/D_m value of approximately 3.0, but since the internal length requirements are always greater than 3.0 (see Appendix B), it was felt that value might place an unncesssarily high drag penalty on the diffuser.

The larger of the two flow rates, cruise or take-off, is used for sizing the diffuser.

The diffuser loss, lip loss, and pipe loss, if any, are calculated for both cruise and take-off. Their sum in each case is used in the equation derived in Appendix A

to determine the critical velocity value at the diffuser exit for cavitation on the elbow turning vane.

$$V_{crit} = \left[\sigma_{oi} + 1 - P_{loss}/\tfrac{1}{2}\rho V_o^2\right]^{\frac{1}{2}} V_o/(1 + \sigma_{tvi})^{\frac{1}{2}}$$

The maximum diffuser exit velocity as determined in chapter 4 is

$$V_{2max} = 1.5\ Q/A_2\ .$$

These two velocities are compared for both conditions. If V_{2max} is greater than V_{crit} for either condition, the subroutine returns to the calling program as before with an arbitralily high weight value. If V_{2max} is satisfactory, the design is complete.

External drag is estimated by

$$D = C_D\ \tfrac{1}{2}\rho V_o^2\ A$$

where A is the external surface area of the nacelle. A is determined by dividing the nacelle in to three sections, the forebody from the nose to the point of tangency with a line parallel to the centerline at maximum diameter, a cylinderical midbody, and a tail section which is assumed to be symmetrical with the forebody. The forebody and tail can be approximated as paraboloids of revolution and their combined area is

$$A_p = (4\pi/3)(D_m/2)^2\ \left[M - 1/(1 - M)\right]$$

where

$$M = \left[1 - 4(2L/D_m)^2\right]^{\frac{1}{2}} \qquad \text{(ref. 4).}$$

For the cylinderical midbody,

$$A_c = \pi(D_m/2)^2\ (L_N - 2L)$$

and then $A = A_p + A_c$.

The drag coefficient is from Hoerner (ref. 15) and is given by

$$C_D = C_f \left[1 + 1.5(D_m/L_N)^{3/2} + 7(D_m/L_N)^3 \right] \ .$$

The Schoenherr friction coefficient, C_f, is calculated by a function subroutine, CFS(R), in which the argument is Reynolds number.

The weight estimate depends on materials and details of the structure which were not the concern of this project. Therefore, only a rough approximation is possible and the assumptions are certainly open to question.

Internal ducting weight was specified to be proportional to the cross sectional area and the length such that $W = 15.07$ (Area) (Length) in pounds where area is in square feet and length in feet (ref. 1).

The weight of the outer envelope is estimated by assuming that it is proportional to the surface area, the maximum wall thickness, and the specific weight. A maximum wall thickness of $0.05D_m$ was used to be consistant with the diffuser exit diameter assumption. The outer envelope of the nacelle, of course, is not solid but is made of inner and outer skins plus stiffening structure. The specific weight depends on the material which has not been specified. Two extremes of the weight spectrum which might be used for such a structure are aluminum and steel. Some material with

a weight between these two is more likely and a material density of one half that of steel was used in the subroutine. The actual weight in water may very well be close to zero if the voids are filled with oil or pitch.

The proportionality constant, a measure of the volume of the material in the wall compared to the volume of the wall itself, a packing factor, will be a small decimal on the order of 0.01 to 0.1. 0.03 was used in the subroutine.

The resulting weight was increased by ten percent to allow for the auxiliary inlet mechanism.

At this point the subroutine's job is completed and it returns to the calling program with the following quantities:

a. the head loss summed from the free stream to the diffuser exit for both speeds, in feet,

b. the drag of two nacelles for both speeds, in pounds,

c. the exit area of two diffusers (one for each nacelle), in square feet,

d. the weight of two nacelles, in pounds,

e. the location of the vertical center of gravity of the nacelles below the keel of the craft, in feet, and

f. the location of the longitudinal center of gravity of the nacelles forward of the transom, in feet.

Chapter 7.

OFF-DESIGN PERFORMANCE

Prediction of off-design performance may be carried out by SUBROUTINE NACEL only after a design has been completed and returned to the calling program. The calling program must reset the value of a control variable named ISTRT from 1 which indicates design, to 3 indicating evaluation, and the value of a control variable named DELTA which has a finite value greater than 1×10^{-9} during design to 0. which prevents rejection and return when cavitation limits are violated.

The same initial values are known as when the design process started, and in addition, all values established during the design cycle are now stored for use during evaluation.

The free stream conditions, total pressure, dynamic pressure and cavitation number, are calcuated for each speed to be evaluated.

The subroutine now proceeds through the same set of calculations as for design except that the auxiliary inlet, and diffuser sizing sections are omitted. Cavitation checks are made in the same manner, but the existing parameters are not allowed to be rejected. Instead of rejection and return a variable named CAV(I,J) has its value changed from 0. to 1. to indicate that cavitation is occuring at the evaluation speed indicated by I and at

the location indicated by J. J=1 on the outside of the forebody, 2 inside the lip, and 3 in the elbow.

On completion of an evaluation cycle the subroutine returns the value of the head loss in feet and the drag in pounds for two nacelles for each of the off-design speeds.

Chapter 8.

CONCLUSIONS AND RECOMMENDATIONS

Results of the subroutine's use with the optimization program are discussed in reference 1. In addition, to test it separately, the subroutine was called by a test program which stepped through values of D_i/D_m from 0.4 to 0.9 and values of cruise V_i/V_o from 0.5 to 1.0 at three cruise speeds, 40, 45 and 50 knots. Take-off speed was assumed to be one half cruise speed. The required flow rate at cruise was arbitrarily set at 600 cubic feet per second with the flow rate at take-off ten per cent greater. The angle of attack was set at two degrees and depth of submergence at five feet.

Ram pressure recovery at the diffuser exit and cavitation limits as calculated from the above input are displayed in Figures 18 through 21. The ram pressure recovery curves are unique to the particular flow rate combination assumed for this calculation and are presented as samples. The cavitation limits would be the same for any flow rate at the same angle of attack and depth of submergence.

Several explicit and implicit assumptions were made in this study to simplify it or to try to bound a realistic value. Further investigation might prove useful in any or all of the following areas:

1. Very little information on bell diffusers that

could be directly applied in this study was found. Conical diffuser performance was assumed to be a lower bound on that expected from a bell. Information on bell diffusers similar to that in reference 11 on other shapes would allow realistic prediction of their performance.

2. The pressure coefficient information used from reference 3 was calculated rather than measured. Although the predicted values for simple cases (i.e., a sphere) was compared with experimental results, no mention is made of comparison of calculated and experimental data for a more complex shape such as an inlet nacelle.

3. The drag calculation was made with the implicit assumption that the drag of a nacelle with a nose inlet and flow into that inlet is very close to the drag of that same body with no nose opening or inflow. References 15, 16 and 17 support this assumption, but only a small number of cases with low D_i/D_m are examined. There is some indication in reference 16 that the range of V_i/V_o for which this assumption holds decreases as D_i/D_m increases.

4. The effect of proximity to the free surface on drag was not included. For overall system performance comparison, the omission of this effect would probably not invalidate the comparison but there could be a slight bias in favor of the smaller nacelle in the case where there is a significant difference in size.

In its present form, SUBROUTINE NACELLE requires interpolation in data tables several times. Some of these tables could be approximated by functions to speed up the operation and reduce computer costs. The data for which this could be carried out include Table 12 and Figure 17. The data in Tables 5 through 16 presents a more difficult problem because the relationship is not single valued in all cases. Perhaps separating it into two or more regions with a different function applicable in each region offers a solution. Some unsuccessful attempts were made to examine possibilities for the large data bank.

One other simplification which would decrease computer time would be accomplished by elimination of the calculation of diffuser length. One of the results of the data run mentioned above was that the diffuser length calculated by iteration in the subroutine was nearly always approximately ninety per cent of the mean of the maximum and minimum allowed values. The equation

$$L_d = 0.9(L_{dmin} + L_{dmax})/2$$

could be used to completely eliminate the iteration.

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Table 1. Geometric Configuration of Kuchemann and Webber Circular Intakes Designated Class A, B and C.

* Dimensions of all three classes are defined by the following equations (adapted from ref. 7, p. 79).

$$Do/Di = K_1$$

$$Dm/2L = K_2 - K_3 \,(Ai/Am)^3$$

$$Di/2Li = 1/K_4 \,(K_1 - 1).$$

Table 1.a Values of the Constants.

Class	K_1	K_2	K_3	K_4
A	1.15	0.2	12.5	1.5
B	1.10	0.2	12.5	1.3
C	1.03	0.2	7.5	1.0

(ref. 7)

Table 1.b Values of the Primary Ratios.

Di/Dm	L/Dm	
	Class A and B	Class C
0.90	0.0732	0.1195
0.80	0.1439	0.231
0.70	0.309	0.452
0.60	0.639	0.910
0.50	1.263	1.575
0.40	2.00	2.175
0.20	2.490	2.494

*(See Fig. 3 for illustration of dimension symbols.)

Table 2. Geometric Configuration of the Lockheed Intakes

Nacelle	*Do/Dm	L/Li	Di/Dm	L/Dm
A-40-550	0.40	9.0	0.333	2.20
A-80-40	0.80	9.0	0.77	0.32
A-50-280	0.50	9.0	0.426	1.40
A-75-60	0.75	9.0	0.713	0.45
A-70-90	0.70	9.0	0.656	0.63
A-55-280	0.55	9.0	0.483	1.54
A-60-135	0.60	9.0	0.541	0.81
A-45-400	0.45	9.0	0.369	1.80
A-60-200	0.60	9.0	0.541	1.20

(ref. 3)

*(See Fig. 3 for illustration of dimension symbols.)

Table 3. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-40-550

Internal Flow:

	Minimum Cp			
Vi/Vo	α=0	2°	4°	6°
0.70	0.420	0.415	0.400	0.390
0.80	0.260	0.250	0.240	0.220
0.90	0.080	0.050	0.045	0.030
1.05	-0.260	-0.255	-0.285	-0.550
1.15	-0.500	-0.510	-0.550	-1.040
1.25	-0.760	-0.765	-1.050	-1.630

External Flow:

0.70	-0.090	-0.110	-0.250	-0.440
0.80	-0.090	-0.090	-0.160	-0.320
0.90	-0.090	-0.090	-0.120	-0.230
1.05	-0.090	-0.090	-0.115	-0.155
1.15	-0.090	-0.090	-0.115	-0.145
1.25	-0.090	-0.090	-0.115	-0.140

(ref. 3)

Table 4. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-80-40

Internal Flow:

	Minimum Cp			
Vi/Vo	$\alpha=0$	2°	4°	6°
0.70	0.200	0.050		
0.80	-0.100	-0.285		
0.90	-0.465	-0.700		
1.05	-1.160	-1.425		
1.15	-1.780	-2.220		
1.25	-2.500	<-2.50		

External Flow:

0.70	-0.435	-0.480	-0.540	-0.60
0.80	-0.420	-0.460	-0.500	-0.560
0.90	-0.405	-0.450	-0.490	-0.515
1.05	-0.375	-0.415	-0.440	-0.475
1.15	-0.365	-0.400	-0.425	-0.460
1.25	-0.350	-0.375	-0.410	-0.440

(ref.3)

Table 5. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-50-280.

Internal Flow:

	Minimum Cp			
Vi/Vo	$\alpha = 0$	2°	4°	6°
0.70	0.380	0.355	0.320	
0.80	0.200	0.160	0.120	
0.90	-0.015	-0.050	-0.100	
1.05	-0.370	-0.420	-0.485	
1.15	-0.640	-0.700	-0.770	
1.25	-0.940	-1.00	-1.080	

External Flow:

0.70	-0.150	-0.160	-0.240	
0.80	-0.150	-0.155	-0.200	
0.90	-0.150	-0.155	-0.190	
1.05	-0.150	-0.155	-0.175	
1.15	-0.150	-0.155	-0.175	
1.25	-0.150	-0.155	-0.175	

(ref. 3)

Table 6. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-75-60

Internal Flow:

	Minimum Cp			
Vi/Vo	α=0	2°	4°	6°
0.70	0.250	0.130	-0.020	
0.80	-0.020	-0.175	-0.350	
0.90	-0.340	-0.530	-0.780	
1.05	-0.930	-1.230	-1.600	
1.15	01.440	-1.815	-2.370	
1.25	-2.050	$<$ -2.50	$<$ -2.50	

External Flow:

0.70	-0.360	-0.390	-0.445	
0.80	-0.350	-0.375	-0.410	
0.90	-0.340	-0.360	-0.395	
1.05	-0.320	-0.345	-0.370	
1.15	-0.310	-0.335	-0.355	
1.25	-0.300	-0.325	-0.345	

(ref. 3)

Table 7. Variation of Minimum Pressure Coefficient with velocity Ratio and Angle of Attack for Lockheed Nacelle A-70-90.

Internal Flow:

	Minimum Cp			
Vi/Vo	α=0	2°	4°	6°
0.70	0.305	0.215	0.100	
0.80	0.070	-0.040	-0.180	
0.90	-0.210	-0.350	-0.535	
1.05	-0.710	-0.930	-1.225	
1.15	-1.130	-1.420	-1.920	
1.25	-1.630	-2.120	$<$ -2.50	

External Flow:

0.70	-0.280	-0.310	-0.375	-0.455
0.80	-0.270	-0.295	-0.335	-0.405
0.90	-0.265	-0.285	-0.315	-0.365
1.05	-0.255	-0.270	-0.300	-0.330
1.15	-0.250	-0.265	-0.290	-0.320
1.25	-0.240	-0.260	-0.280	-0.310

(ref. 3)

Table 8. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-55-280.

Internal Flow:

	Minimum Cp			
Vi/Vo	α =0	2°	4°	6°
0.70	0.415	0.385	0.350	
0.80	0.235	0.200	0.160	
0.90	0.030	-0.010	-0.070	
1.05	-0.330	-0.375	-0.440	
1.15	-0.595	-0.650	-0.780	
1.25	-0.880	-0.950	-1.380	

External Flow:

0.70	-0.125	-0.225	-0.450	-0.700
0.80	-0.125	-0.145	-0.270	-0.500
0.90	-0.125	-0.135	-0.185	-0.320
1.05	-0.125	-0.130	-0.170	-0.205
1.15	-0.125	-0.130	-0.150	-0.190
1.25	-0.125	-0.130	-0.150	-0.170

(ref. 3)

Table 9. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-60-135

Internal Flow:

	Minimum Cp			
Vi/Vo	$\alpha = 0$	2°	4°	6°
0.70	0.300	0.230	0.140	0.040
0.80	0.080	-0.010	-0.115	-0.235
0.90	-0.175	-0.280	-0.405	-0.560
1.05	-0.620	-0.755	-0.910	-1.135
1.15	-0.965	-1.120	-1.330	-1.620
1.25	-1.340	-1.535	< -1.80	-2.230

External Flow:

0.70	-0.255	-0.280	-0.315	-0.380
0.80	-0.255	-0.275	-0.300	-0.350
0.90	-0.250	-0.270	-0.295	-0.330
1.05	-0.245	-0.265	-0.280	-0.310
1.15	-0.240	-0.265	-0.280	-0.300
1.25	-0.240	-0.260	-0.275	-0.295

(ref. 3)

Table 10. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-45-400

Internal Flow:

	Minimum Cp			
Vi/Vo	α=0	2°	4°	6°
0.70	0.400	0.385	0.370	
0.80	0.230	0.205	0.185	
0.90	0.025	0.000	-0.020	
1.05	-0.320	-0.340	-0.365	
1.15	-0.570	-0.600	-0.630	
1.25	-0.850	-0.880	-0.915	

External Flow:

0.70	-0.120	-0.140	-0.310	
0.80	-0.120	-0.130	-0.210	
0.90	-0.120	-0.130	-0.155	
1.05	-0.120	-0.130	-0.150	
1.15	-0.120	-0.130	-0.150	
1.25	-0.120	-0.130	-0.150	

(ref. 3)

Table 11. Variation of Minimum Pressure Coefficient with Velocity Ratio and Angle of Attack for Lockheed Nacelle A-60-200

Internal Flow:

	Minimum Cp			
Vi/Vo	$\alpha=0$	2°	4°	6°
0.70	0.400	0.360	0.300	
0.80	0.205	0.150	0.075	
0.90	-0.015	-0.080	-0.165	
1.05	-0.400	-0.485	-0.620	
1.15	-0.685	-0.800	-1.140	
1.25	-1.000	-1.265	-1.890	

External Flow:

0.70	-0.160	-0.200	-0.385	-0.660
0.80	-0.160	-0.175	-0.240	-0.420
0.90	-0.160	-0.160	-0.210	-0.280
1.05	-0.160	-0.160	-0.185	-0.230
1.15	-0.160	-0.160	-0.180	-0.215
1.25	-0.160	-0.160	-0.180	-0.210

(ref. 3)

Table 12. Pressure Loss Coefficient for an Elliptical Profile Lip

Vi/Vo	$\Delta P/qo$
0.6	0.025
0.8	0.033
1.0	0.043
1.2	0.085
1.4	0.130
1.6	0.173

Reynold's number $\simeq 8 \times 10^4$

(Adapted from Fig. 74, Report No. 5, ref. 3)

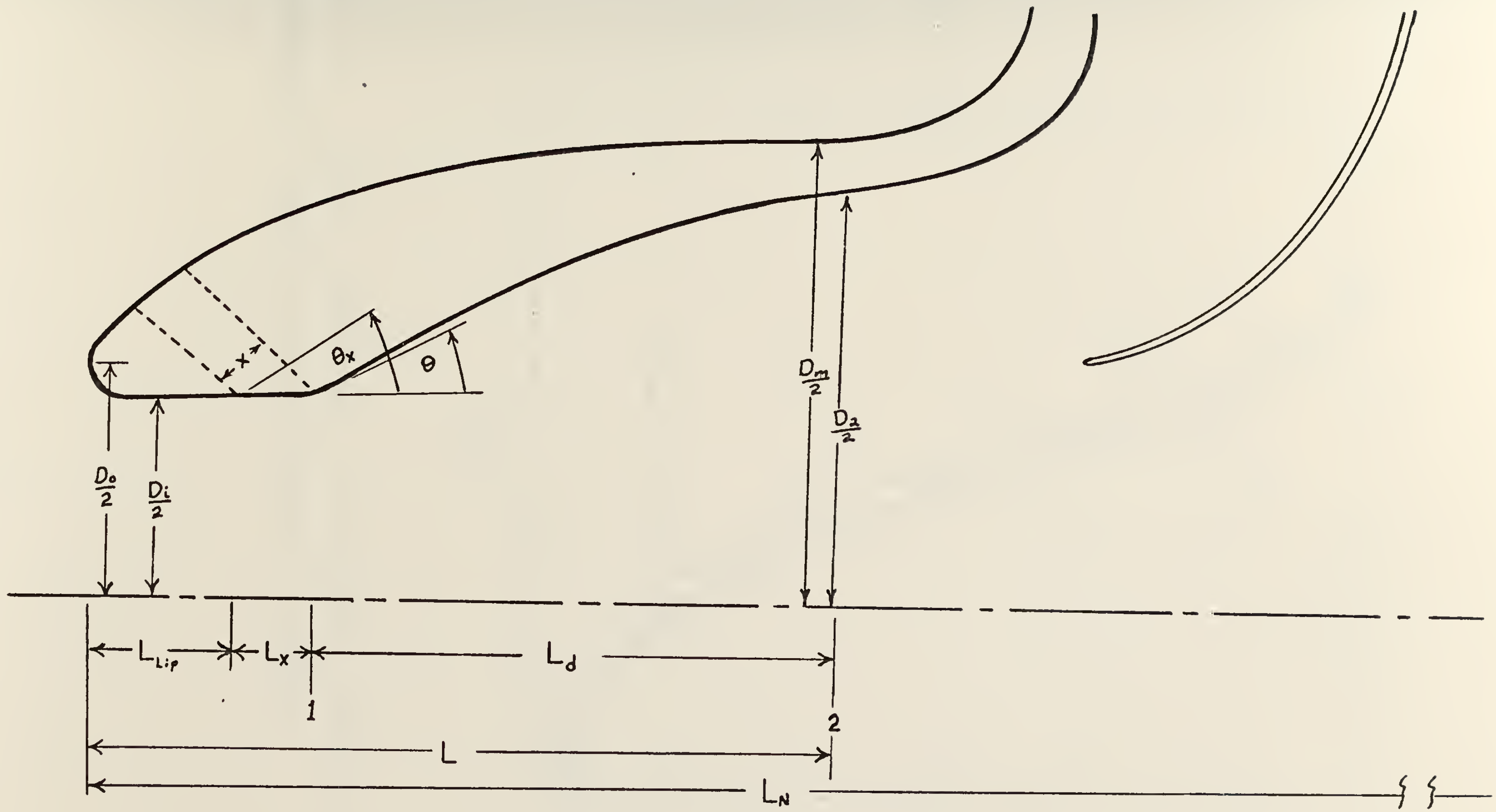


Figure 3. Nacelle Geometry

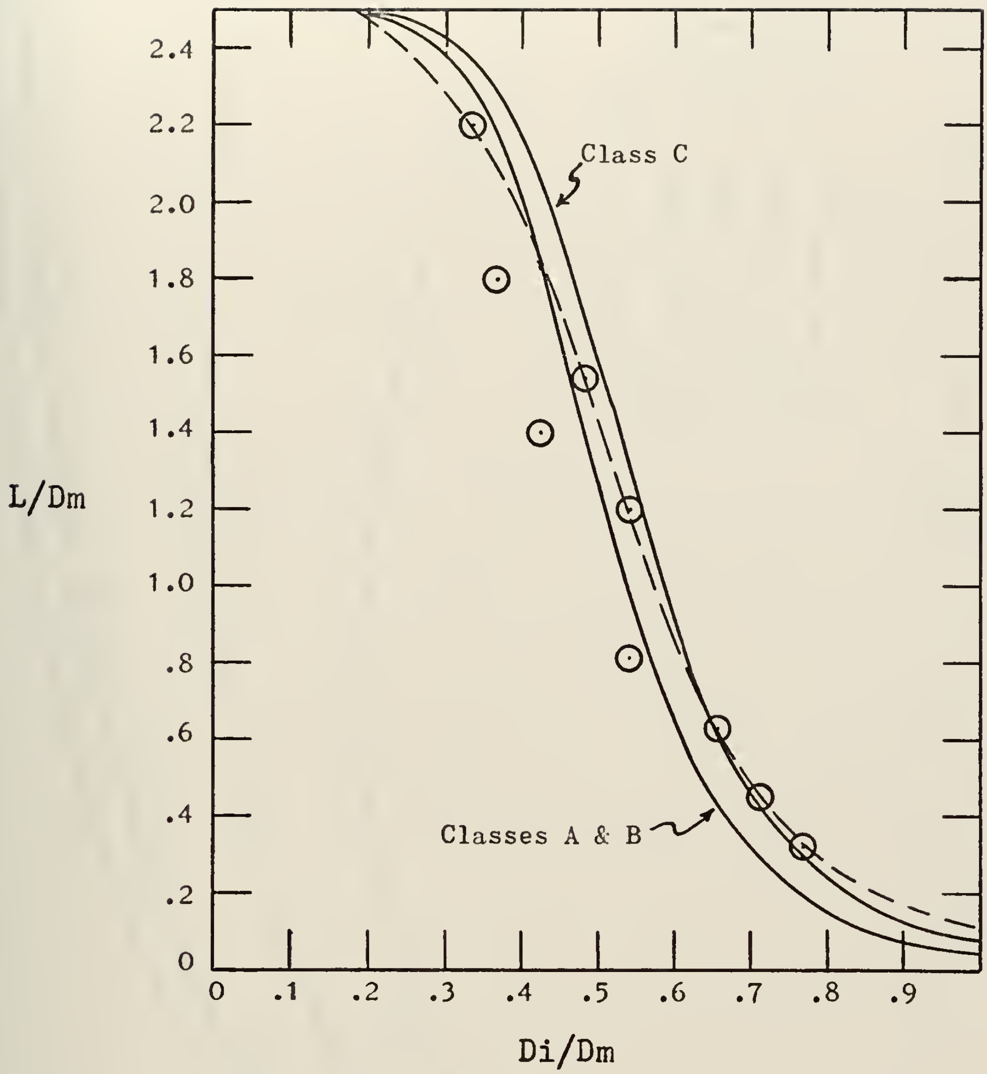


Figure 4. L/Dm vs. Di/Dm for the Lockheed intakes and Kuchemann and Weber intakes Classes A, B and C.

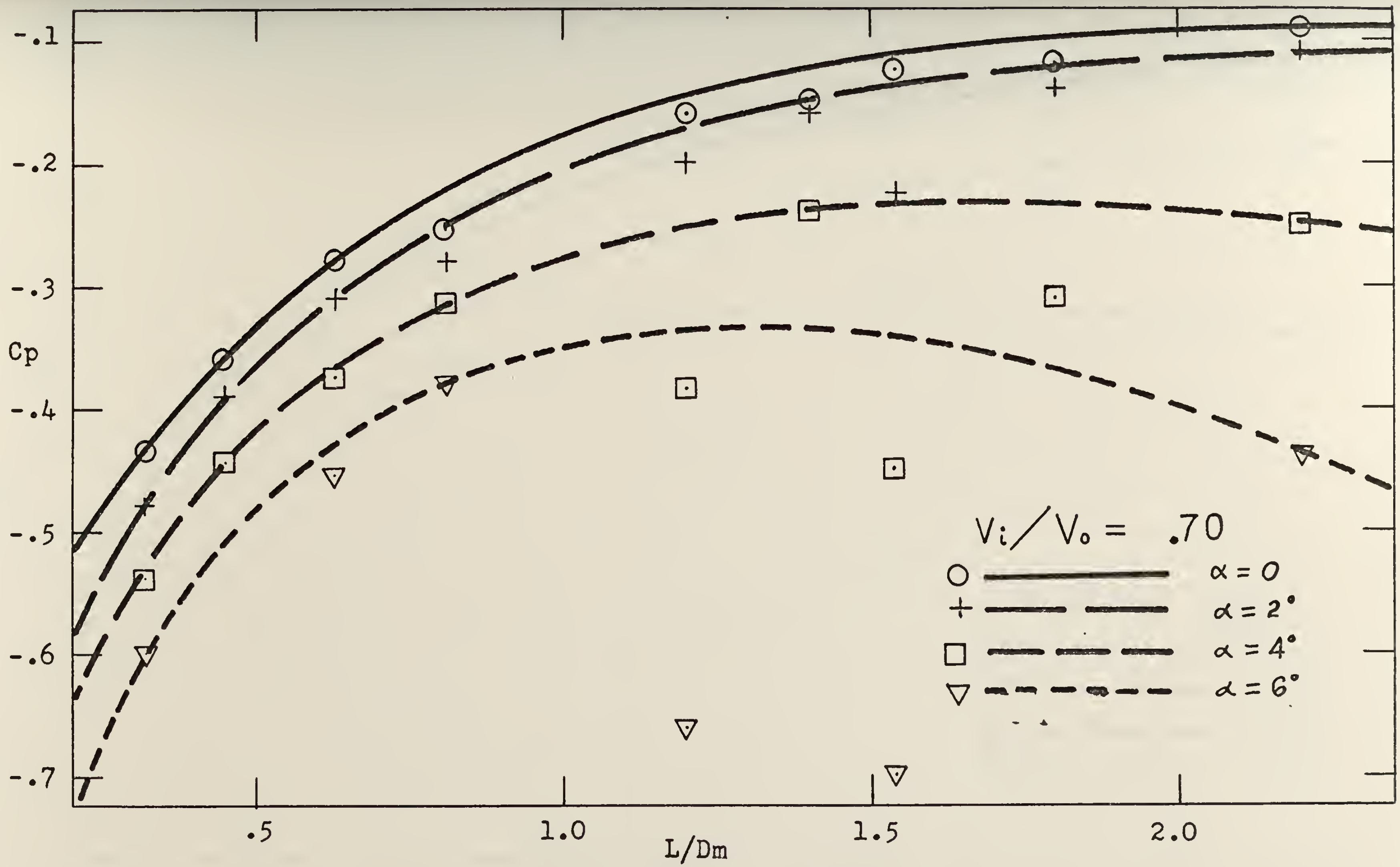


Figure 5. Minimum Cp vs. L/Dm in the external flow at Vi/Vo = .70

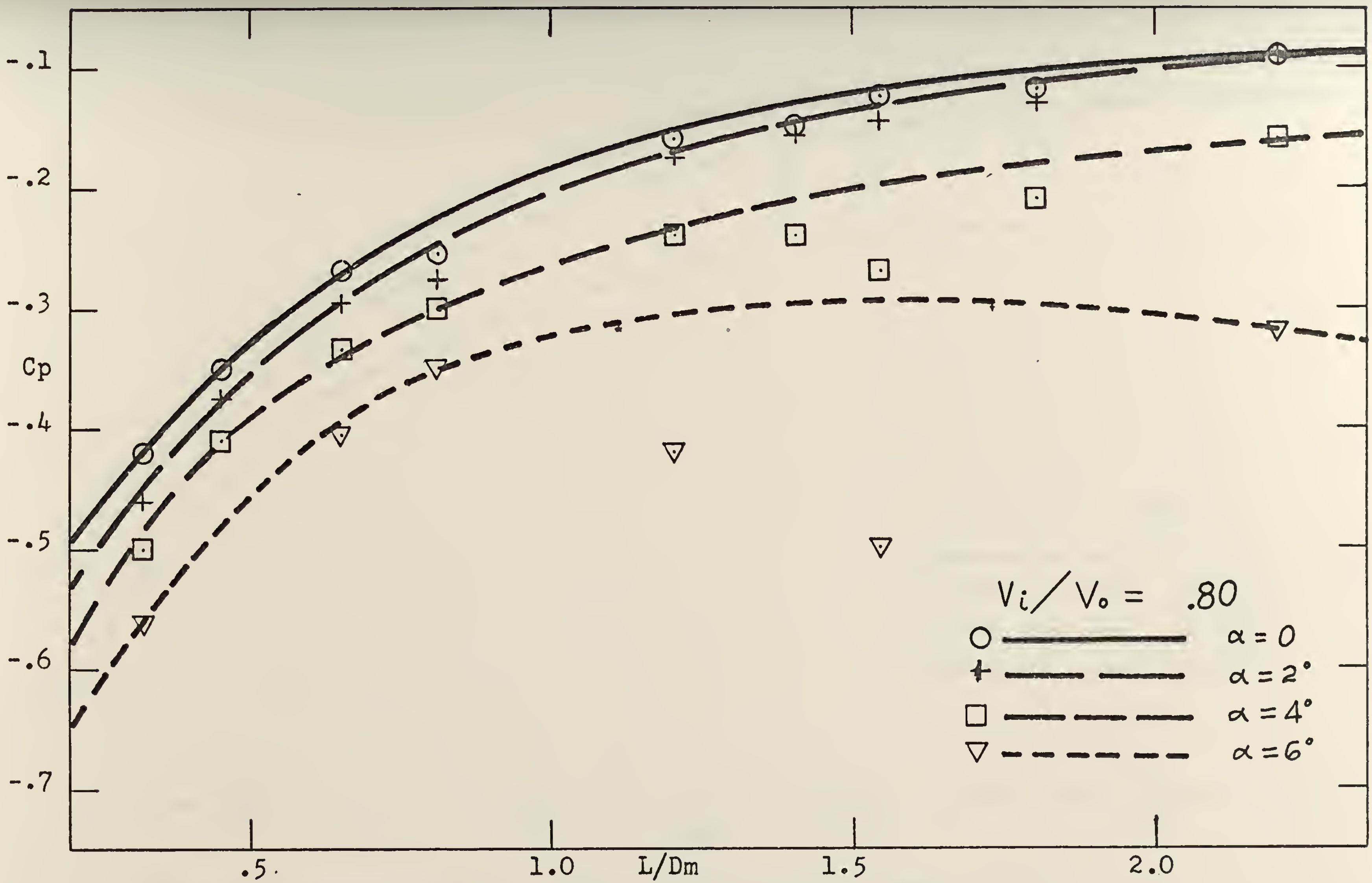


Figure 6. Minimum Cp vs. L/Dm in the external flow at Vi/Vo = .80

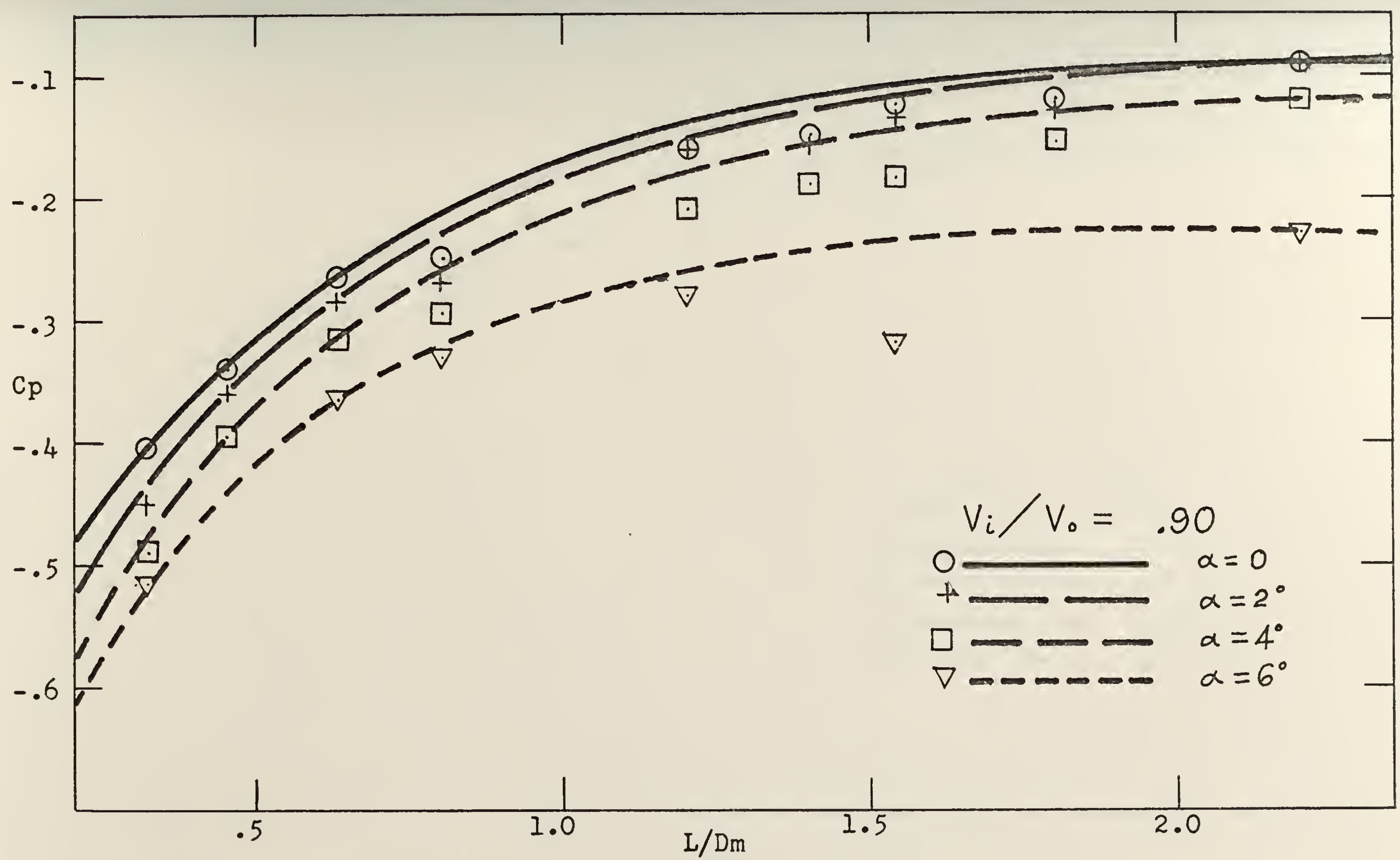


Figure 7. Minimum Cp vs. L/Dm in the external flow at Vi/Vo = .90

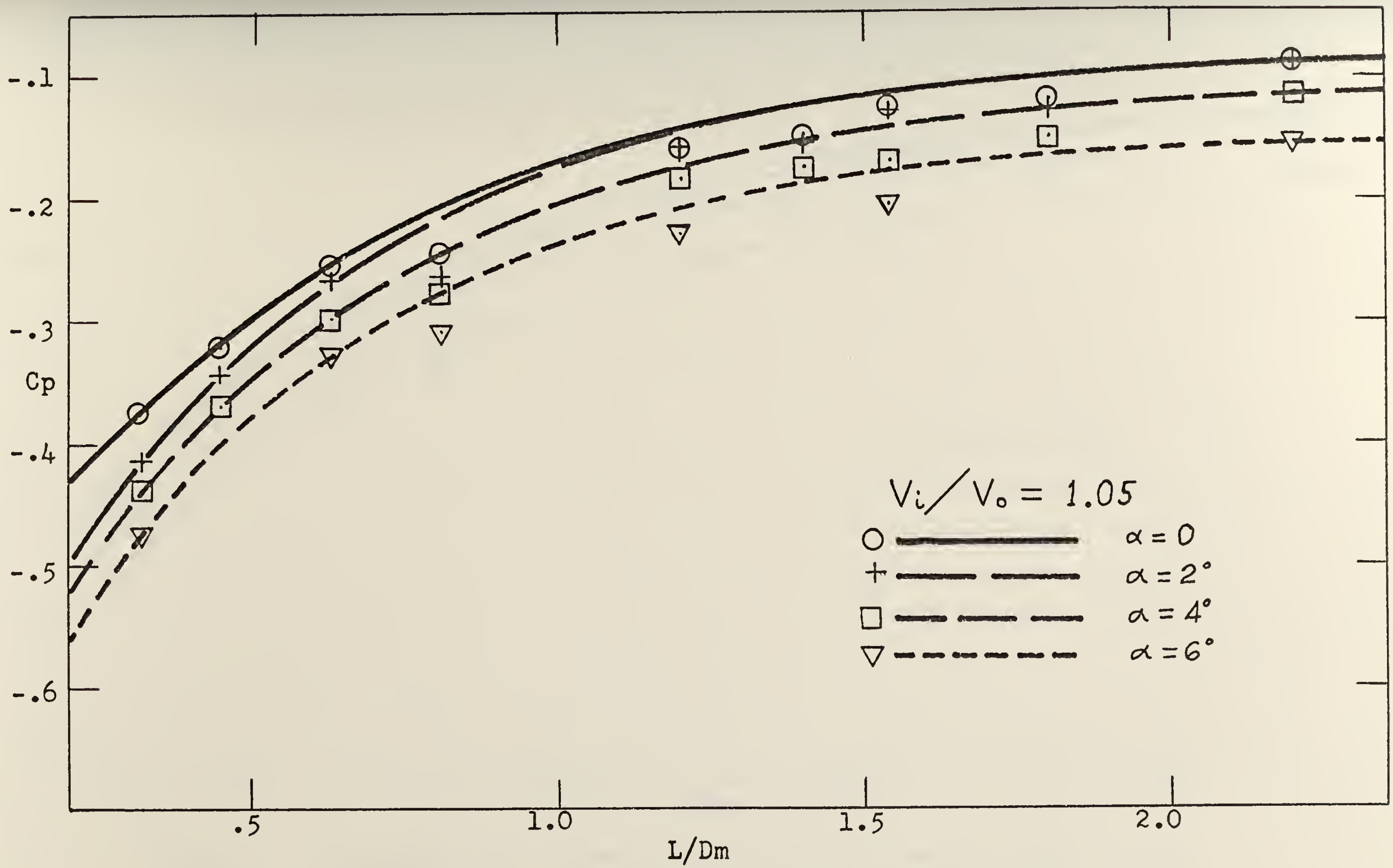


Figure 8. Minimum Cp vs. L/Dm in the external flow at Vi/Vo = 1.05

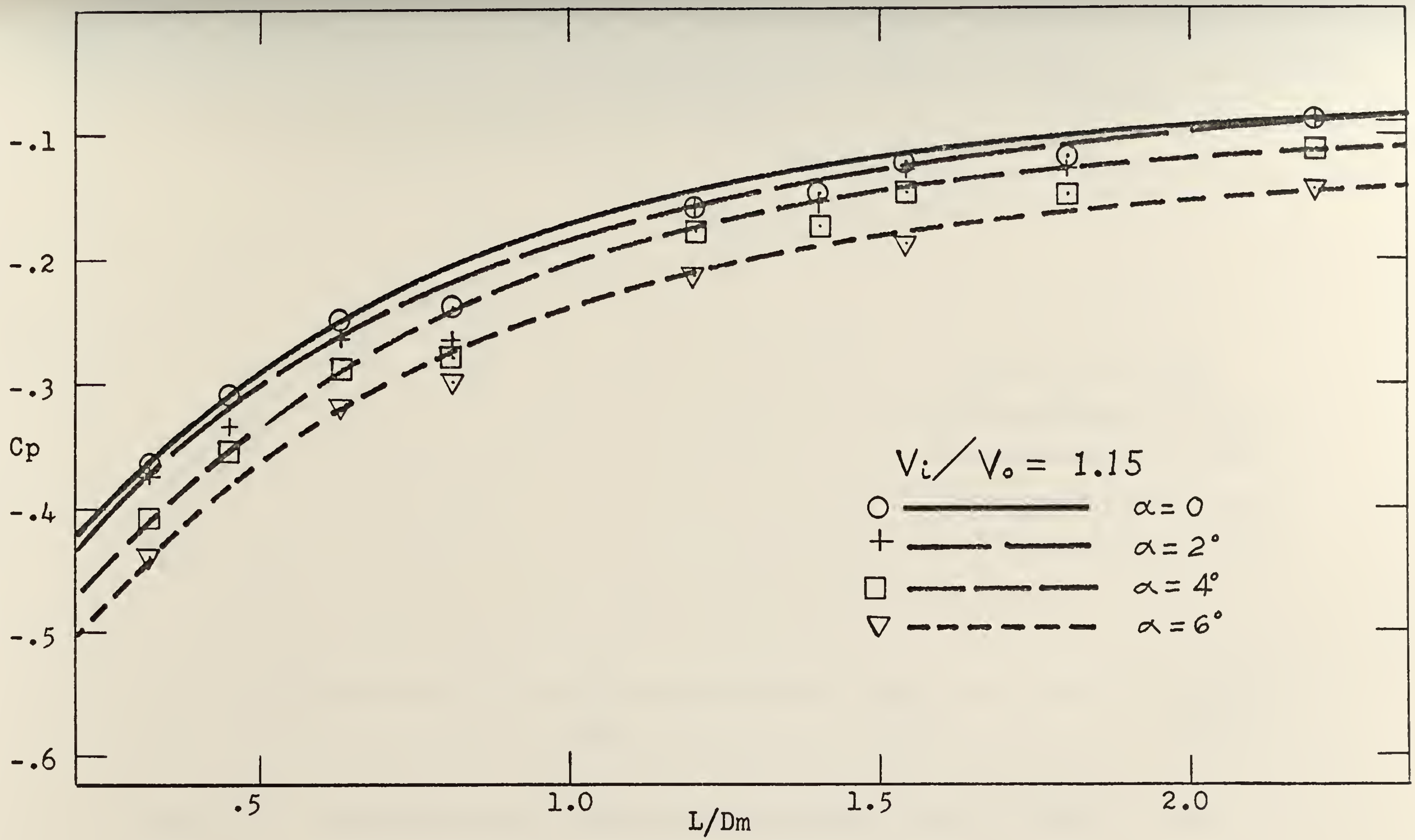


Figure 9. Minimum Cp vs. L/Dm in the external flow at Vi/Vo = 1.15

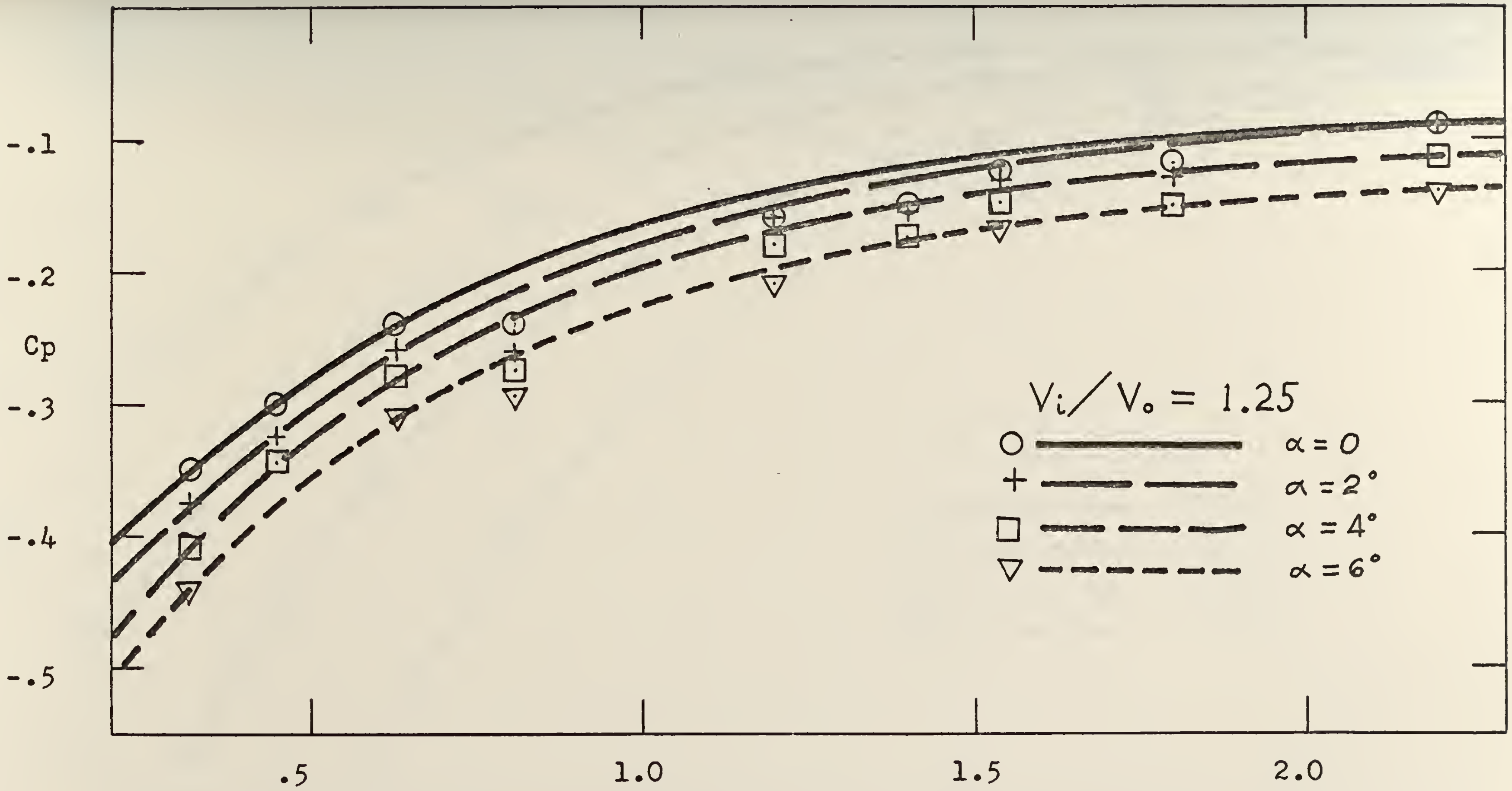


Figure 10. Minimum Cp vs. L/Dm in the external flow at Vi/Vo = 1.25

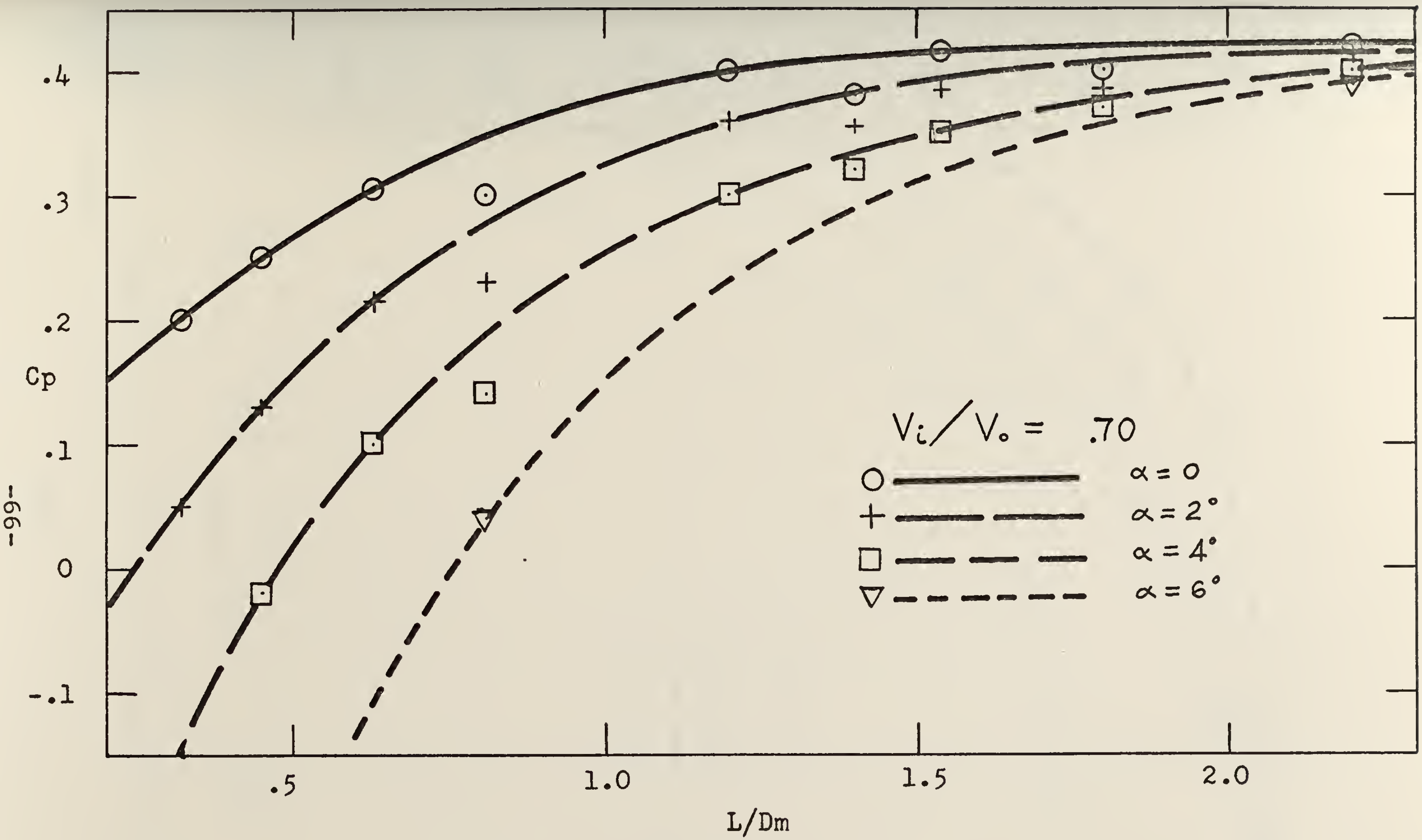


Figure 11. Minimum Cp vs. L/Dm in the internal flow at Vi/Vo = .70

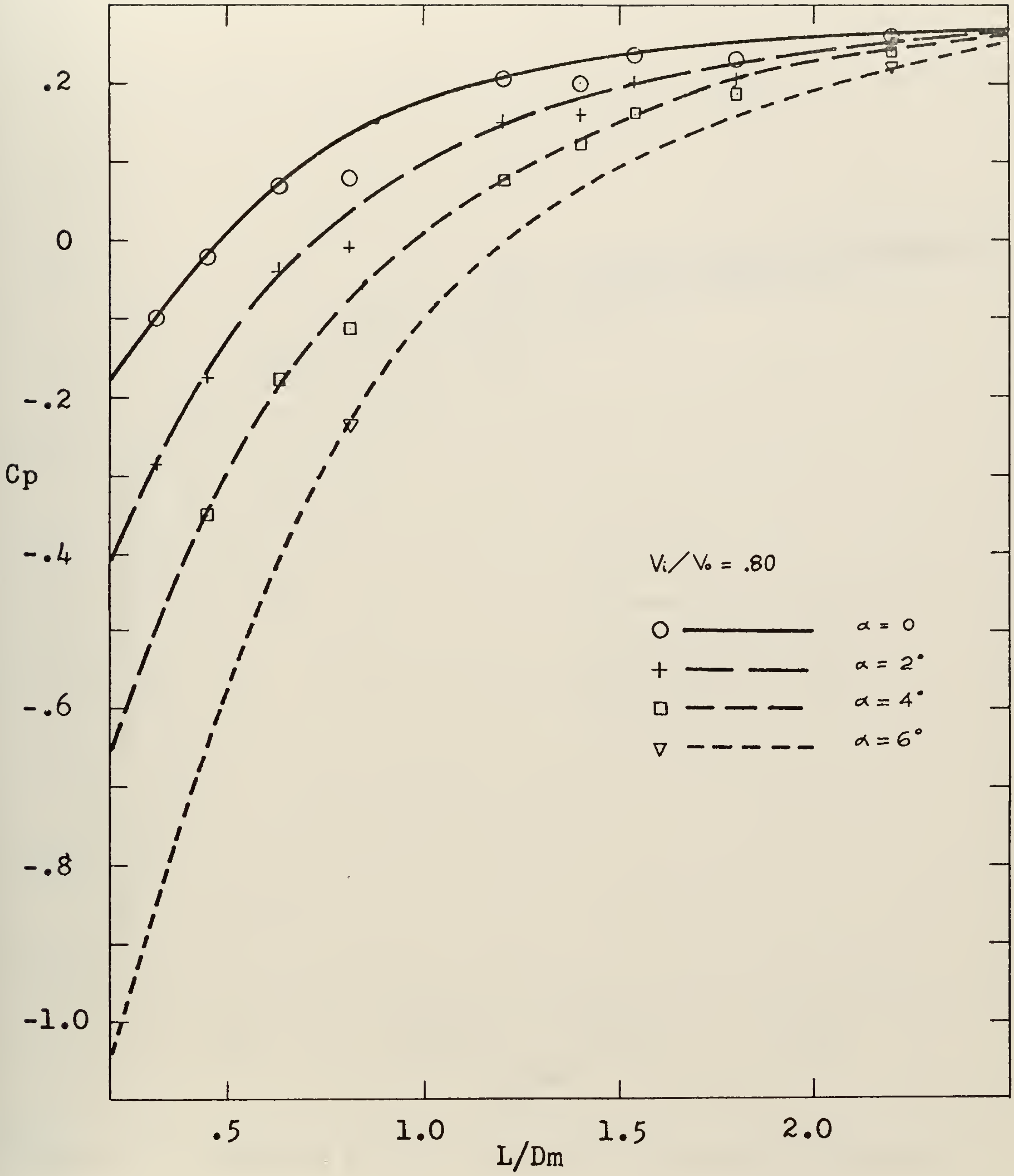


Figure 12. Minimum Cp vs. L/Dm in the internal flow at Vi/Vo = .80

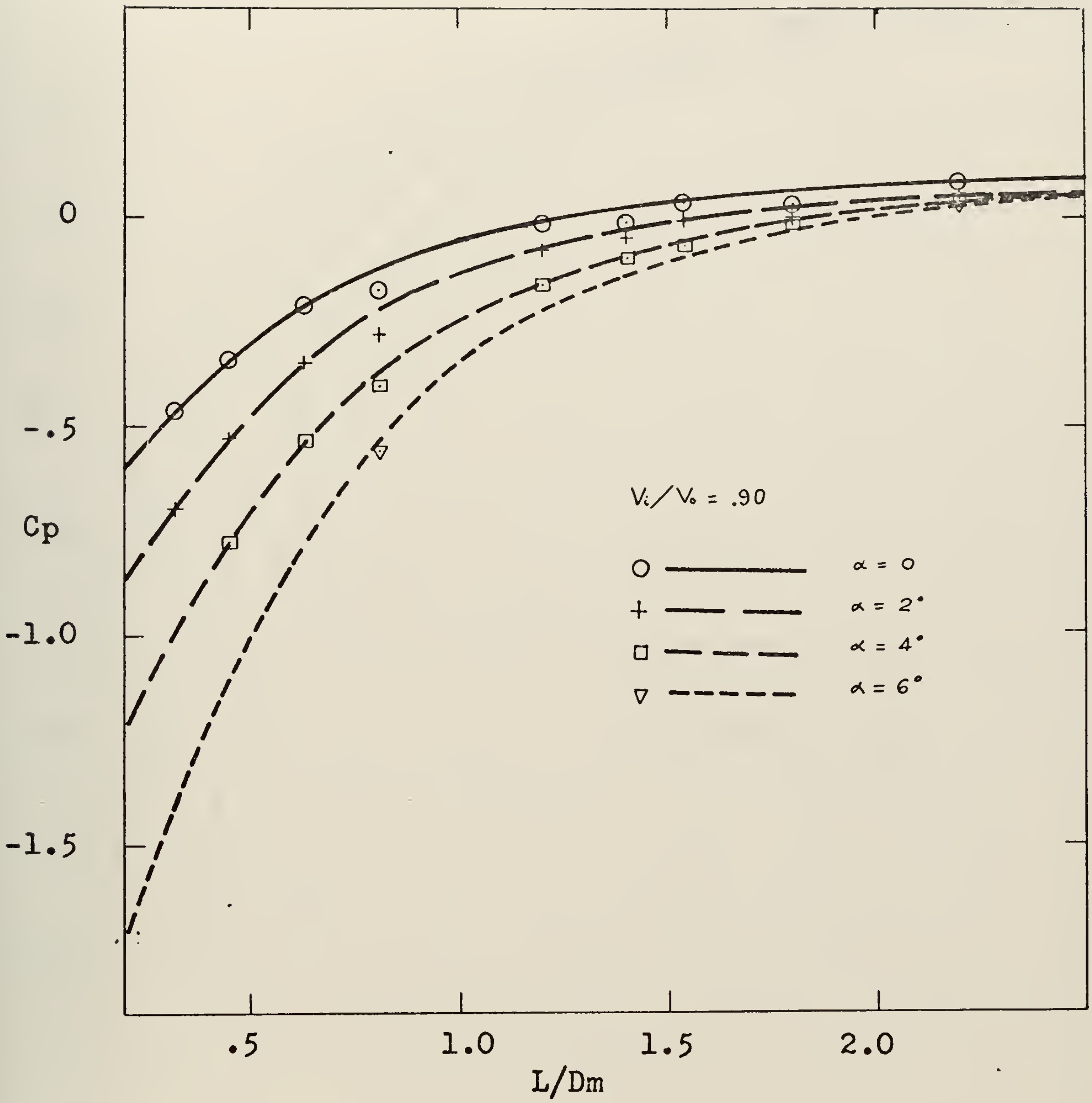


Figure 13. Minimum Cp vs. L/Dm in the internal flow at Vi/Vo = .90

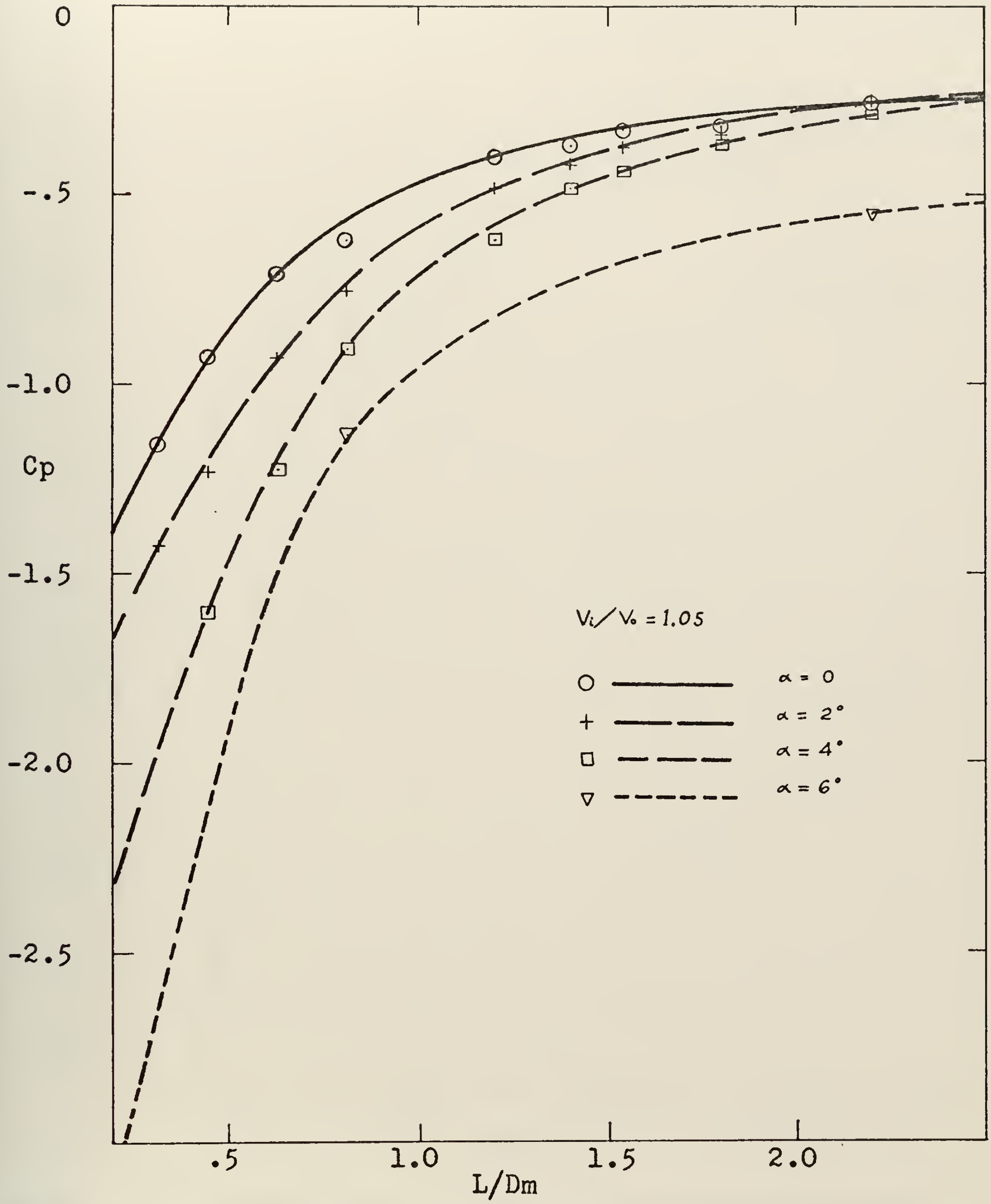


Figure 14. Minimum Cp vs. L/Dm in the internal flow at Vi/Vo = 1.05

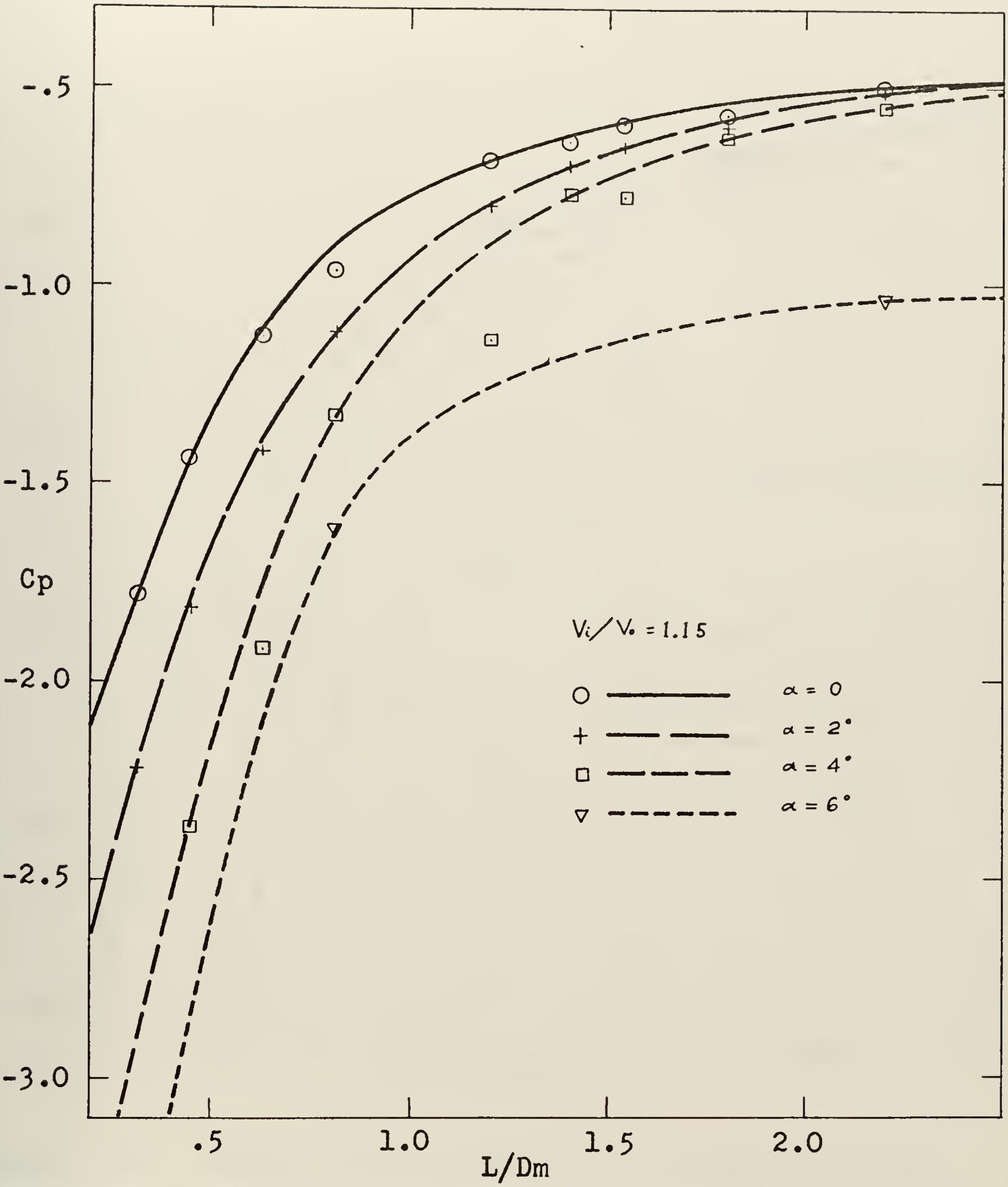


Figure 15. Minimum Cp vs. L/Dm in the internal flow at Vi/Vo = 1.15

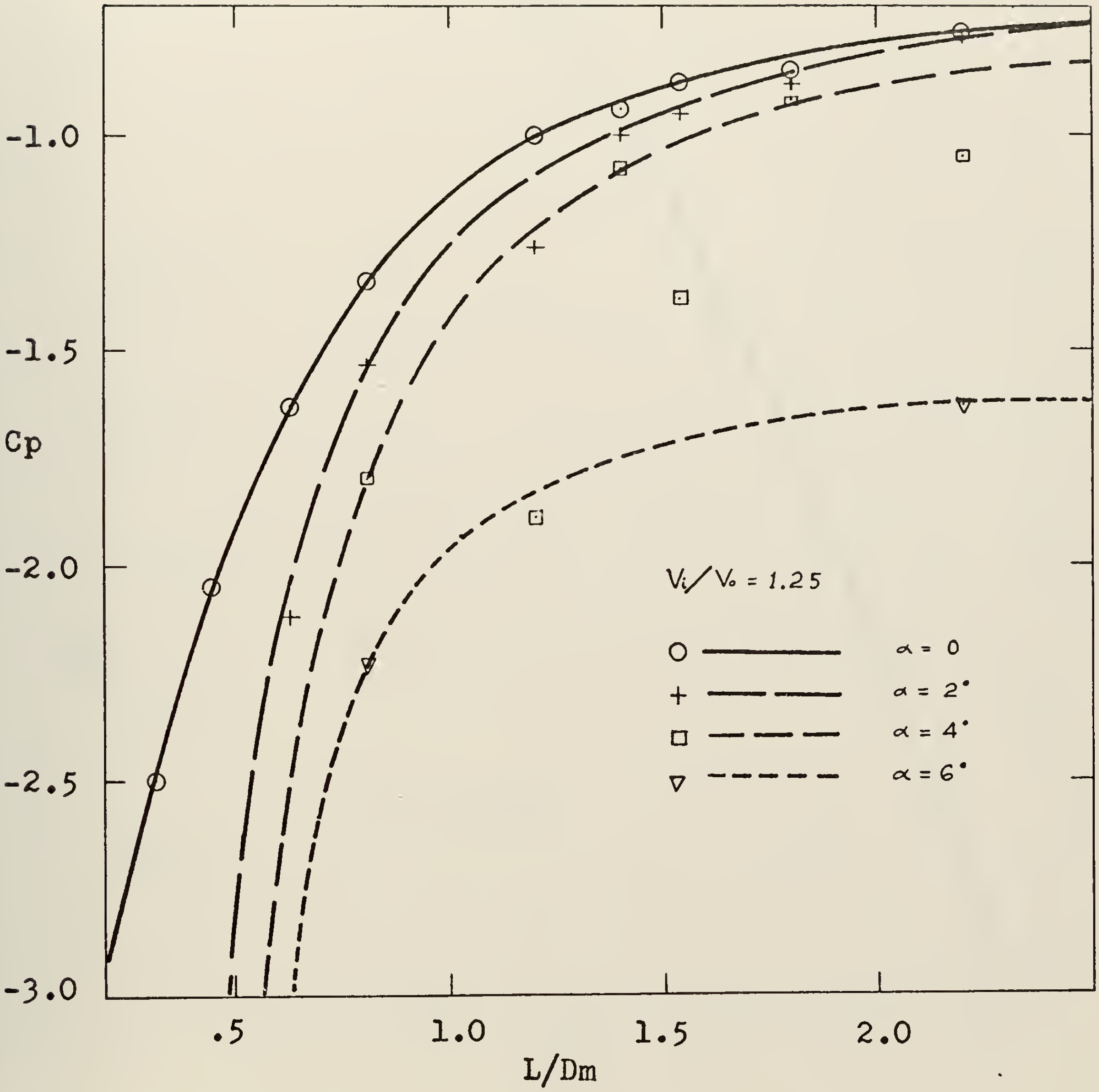


Figure 16. Minimum Cp vs. L/Dm in the internal flow at Vi/Vo = 1.25

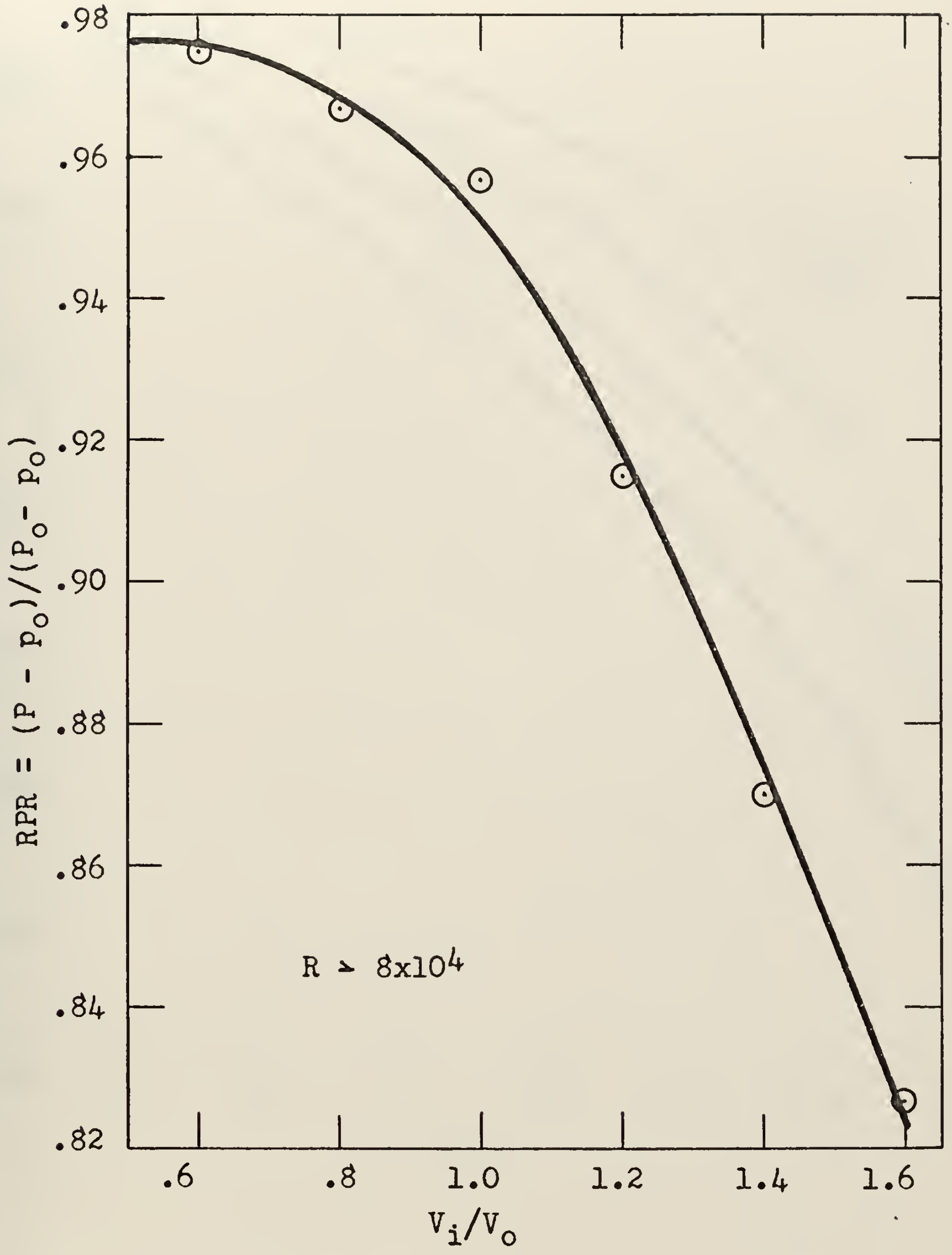


Figure 17. Ram Pressure Recovery vs. V_i/V_o for the elliptical profile lip (Blackaby and Watson 18E).

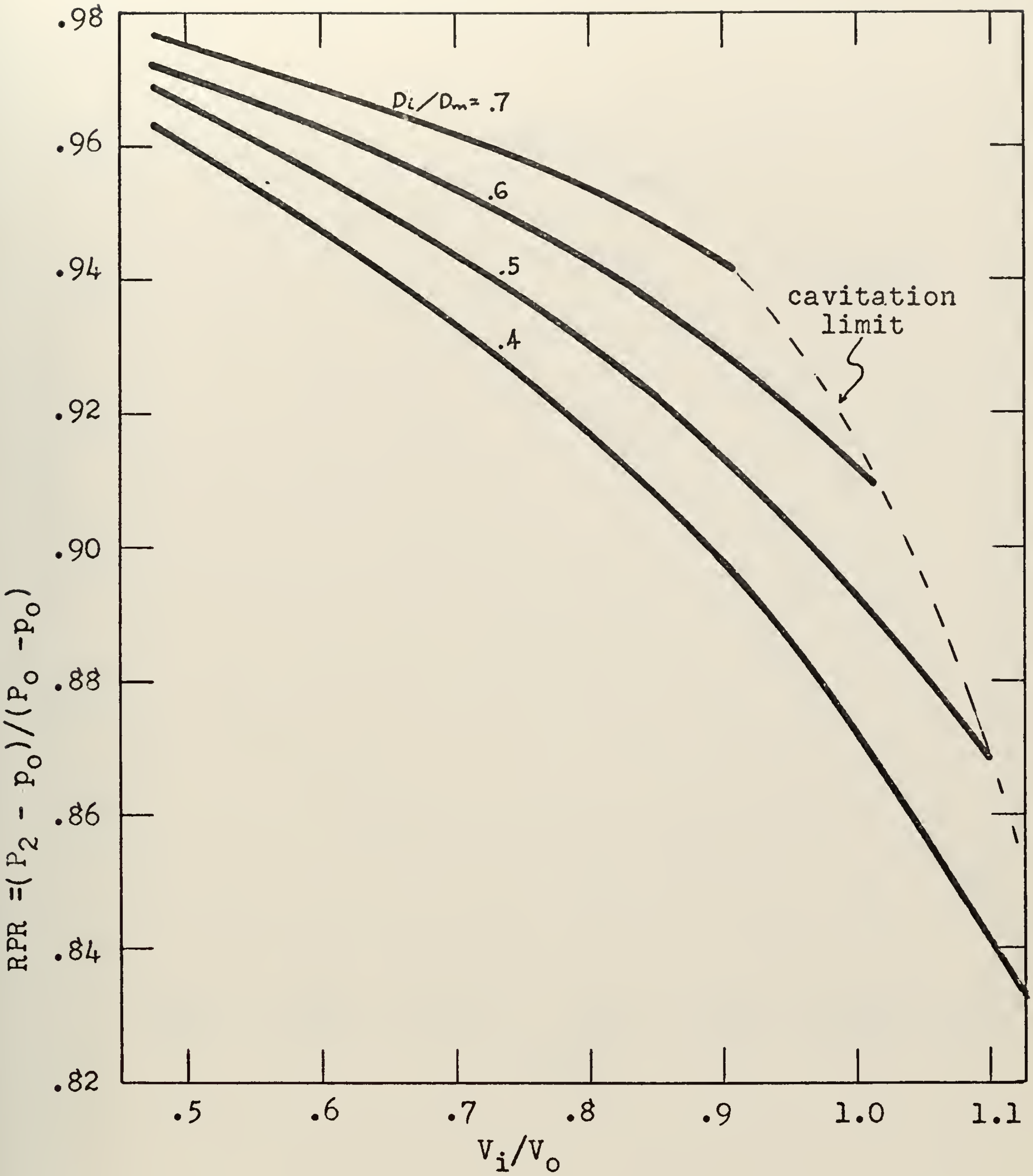


Figure 18. Ram Pressure Recovery at the diffuser exit vs. V_i/V_o for a 40 knot cruise speed

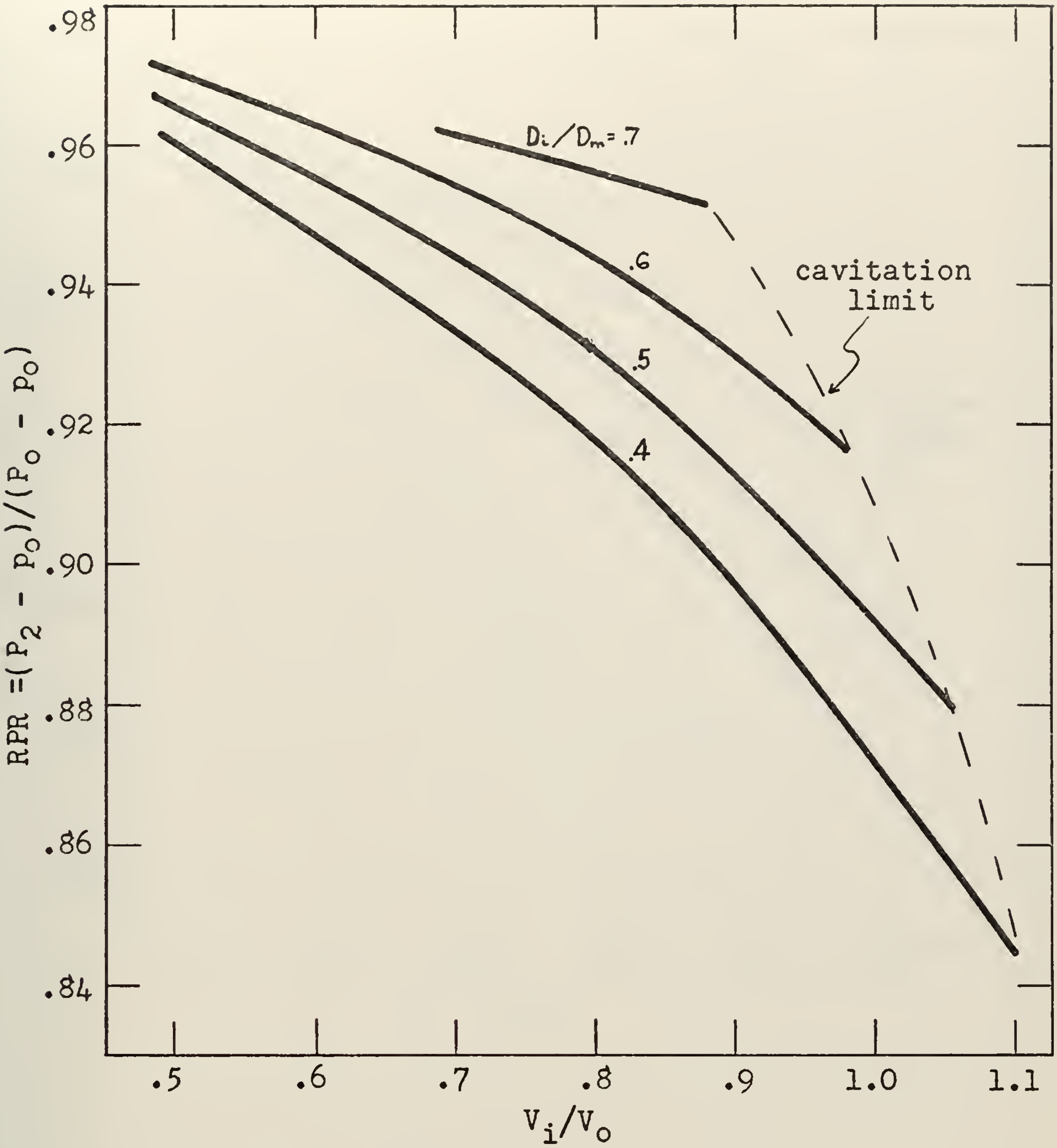


Figure 19. Ram Pressure Recovery at the diffuser exit vs. V_i/V_o for a 45 knot cruise speed

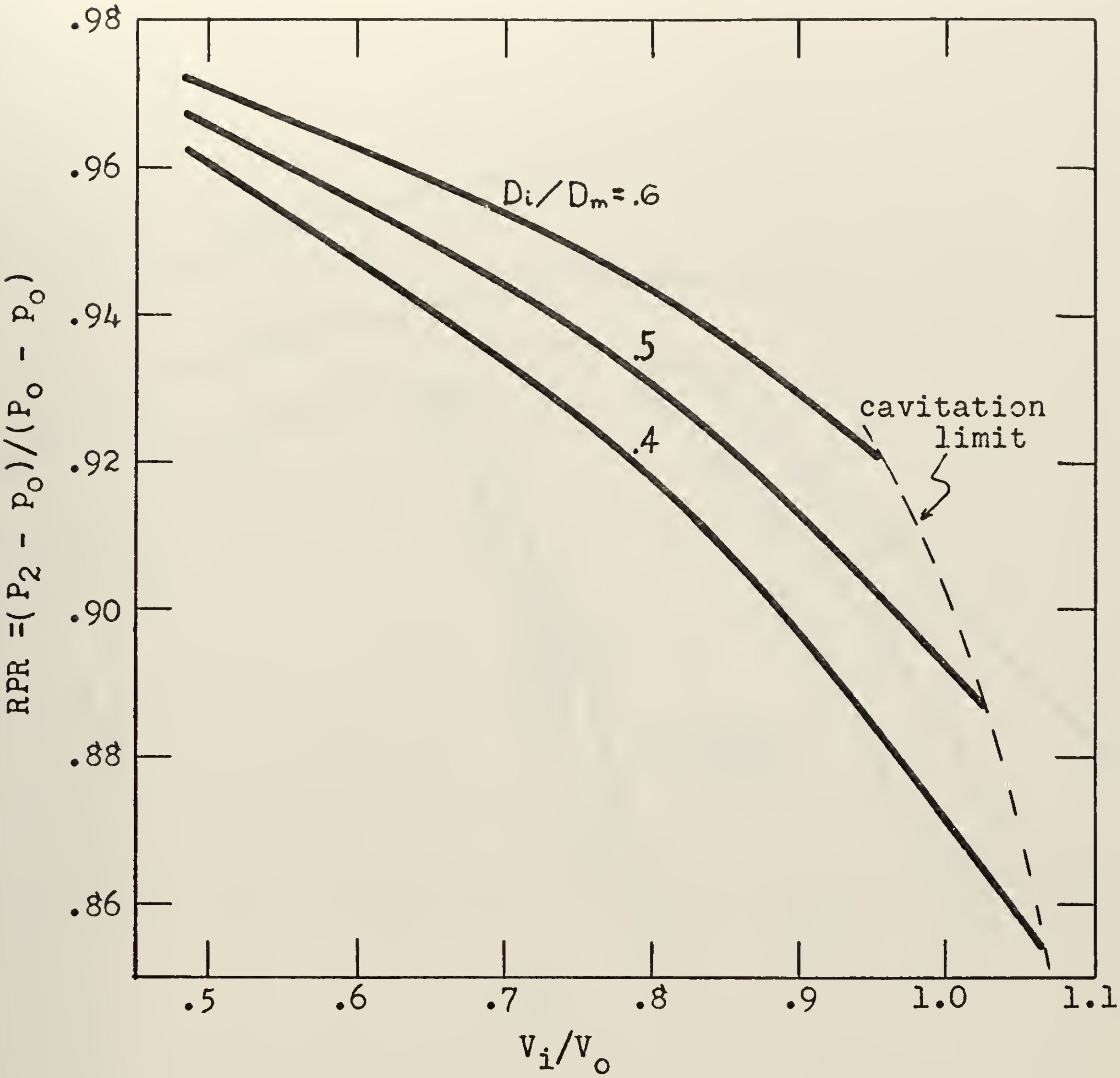


Figure 20. Ram Pressure Recovery at the diffuser exit vs. V_i/V_o for a 50 knot cruise speed

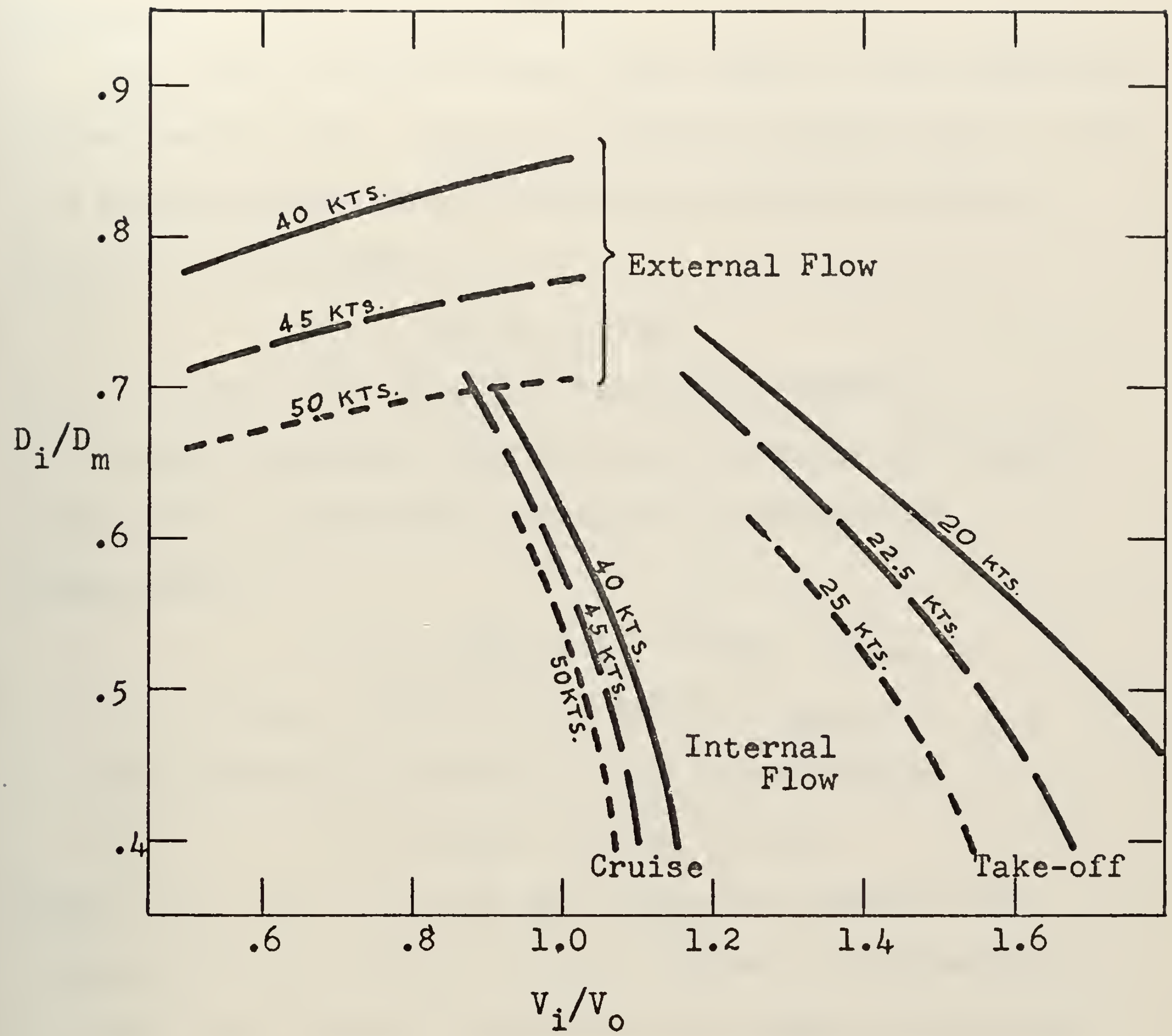


Figure 21. Cavitation limits as a function of D_i/D_m vs. V_i/V_o at cruise speeds of 40, 45 and 50 knots

Appendix A. CAVITATION CRITERA

The total pressure head at any point in the system can be determined with respect to the free stream head by tracing along a stream line from out in the free stream to the point of interest.

$$H = H_o - H_{loss}$$

or $P = P_o - P_{loss}$ in terms of pressure.

Using Bernoulli's equation and allowing the static head term to reflect all changes in elevation or submergence,

$$h_o - V_o^2/2g = h - V^2/2g - H_{loss}$$

$$\text{or } p_o + \tfrac{1}{2}\rho V_o^2 = p + \tfrac{1}{2}\rho V^2 + P_{loss}.$$

The cavitation number, σ, can be defined as

$$\sigma \equiv (P_{ref.} - p)/\tfrac{1}{2}\rho V^2_{ref.}$$

Where $P_{ref.}$ and $V_{ref.}$ are the reference pressure and velocity to which the cavitation number is related and p is the local static pressure at the point of interest.

If the free stream conditions are used for reference, then p_o and V_o are the reference pressure and velocity. In this case

$$p_o - p = \tfrac{1}{2} \quad V^2 - \tfrac{1}{2} \quad V_o^2 + P_{loss}$$

$$\text{so } \sigma_o = (p_o - p)/\tfrac{1}{2}\rho V_o^2 = V^2/V_o^2 - 1 + P_{loss}/\tfrac{1}{2}\rho V_o^2$$

Cavitation is assumed to occur when the local static pressure is equal to the vapor pressure of water. The incipient free stream cavitation number is defined by

$$\sigma_{oi} \equiv (p_o - p_v)/\tfrac{1}{2}\rho V_o^2 = (V_{crit}/ V_o^2)-1 + P_{loss}/\tfrac{1}{2}\rho V_o^2.$$

This definition allows the prediction of cavitation using the free stream incipient cavitation number if the losses are known.

Consider the situation in Figure (3). The diffuser entry is designated station 1, and the diffuser exit station 2, to remain consistant with the rest of the text. The turning vane is not intended to be a particular type or design, but is expected to be well designed and sized for the elbow and diffuser with which it is used. The sketch is conceptual, only. The subscript tv will designate conditions on the turning vane.

To determine the cavitation number on the turning vane, conditions at station 2 can be used and, in turn, related to the free stream. As before,

$$P_{tv} = P_2 - P_{\substack{loss \\ 2 \rightarrow tv}}$$

If the turning vane starts near station 2, then any loss between there and the point of lowest pressure can be neglected as it will be very close to the leading edge.

$$P_{tv} = P_2 = p_{tv} + \tfrac{1}{2}\rho V_{tv}^2 = p_2 + \tfrac{1}{2}\rho V_2^2$$

The cavitation number on the turning vane is,

$$\sigma_{tv} = (p_2 - p_{tv})\tfrac{1}{2}\rho V_2^2.$$

When $p_{tv} = p_v$, cavitation starts, so the incipient cavitation number is

$$\sigma_{tvi} = (p_2 - p_v)/\tfrac{1}{2}\rho V_2^2.$$

σ_{tvi} is a characteristic number determined from

experiments and is therefore known (ref. 28). The conditions at station 2 which will cause cavitation on the turning vane can be determined. Solving the equation above for p_2,

$$p_2 = \sigma_{tvi} \tfrac{1}{2}\rho V_2^2 + p_v,$$

but p_2 can be determined in terms of the free stream conditions, which are known.

$$p_2 = p_o + \tfrac{1}{2}\rho V_o^2 - \tfrac{1}{2}\rho V_2^2 - P_{loss}$$

$$\text{or} \quad \sigma_{tvi} \tfrac{1}{2}\rho V_2^2 + p_v = p_o + \tfrac{1}{2}\rho V_o^2 - \tfrac{1}{2}\rho V_2^2 - P_{loss}$$

P_{loss} in this expression is the sum of all losses from the free stream to station 2. V_2 is the only variable remaining which indicates the conditions at station 2, so solving for V_2^2,

$$V_2^2 (1 + \sigma_{tvi}) = \left[(p_o - p_v)/\tfrac{1}{2}\rho V_o^2 + 1 - P_{loss}/\tfrac{1}{2}\rho V_o^2\right] V_o^2$$

The first term in the brackets is the free stream incipient cavitation number. The value of V_2 which gives rise to incipient cavitation on the turning vane is

$$V_2 = \left[\sigma_{oi} + 1 - P_{loss}/\tfrac{1}{2}\rho V_o^2\right]^{\frac{1}{2}} V_o / (1 + \sigma_{tvi})^{\frac{1}{2}}.$$

Appendix B. GEOMETRIC DERIVATIONS

There are three variable lengths in the nacelle which are not a function of the forebody geometry and which must be calculated in each design. They are the diffuser length, L_d, the additional length due to the auxiliary inlet, L_X, and a length after the diffuser exit containing part of the elbow which directs the flow upward into the strut, the strut inlet length.

1. The Strut Inlet Length

Assume that the thickness to chord ratio of the strut all along its length from the nacelle to the free surface is determined by the criterion

$$t_m/c_o = \left[(1 + \sigma_i)^{\frac{1}{2}} - 1\right]/1.15 \qquad \text{(ref. 1,4)}$$

where σ_i is the local free stream incipient cavitation number. Also assume an elliptical cross section for the strut and a rectangular cross section for the internal ducting (ref. 1).

The respective areas are

$$A_{strut} = (\pi/4)\ t_m\ c_o$$

$$A_{duct} = \tfrac{1}{2}\ t_m\ c_o \qquad \text{(ref. 1)} \quad .$$

A_{duct} must be the same as the exit area of the diffuser, A_2.

To allow for structure and fairing, assume that the desired additional nacelle length is close to the value of the strut chord, c_o.

For $\sigma_i = 0.3$, $t_m = 0.12\ c_o$, $2A_2 = 0.12\ c_o^2$, so that

$$c_o = 3.545\ D_2 \quad .$$

2. Length Due to the Auxiliary Inlet

If the auxiliary inlet has the configuration shown in Figure 3, the inlet area is a section of a right circular cone with a minimum diameter D_i, and slant height X.

The angle of inclination from the centerline of that cone section, shown in the figure as θ_x, is assumed to be formed between the centerline and a line passing through the nose leading edge to the point of tangency of the forebody at maximum diameter, D_m.

$$\theta_x = \tan^{-1}\left[(D_m - D_i)/2L\right]$$

The mean diameter of the conical section is then

$$D = D_i + X \sin \theta_x$$

and its area is

$$A_{cone} = \pi D X \quad .$$

The area of the inlet will actually be some percentage of the area above because some allowance must be made for structure.

$$A_{Aux} = K \pi D X$$

K = 0.8 is used in the subroutine.

Finally, solving for X in the above expression,

$$X = (0.5/\sin O_x)\left[(D_i^2 + 1.273\ A_{Aux} \sin \theta_x/K)^{\frac{1}{2}} - D_i\right] \; ,$$

and $$L_x = X/\cos \theta_x \quad .$$

3. Diffuser Length

The length of the diffuser, L_d, becomes a factor in the determination of nacelle length when the sum of the

internal lengths exceeds the minimum length, $5.5D_m$. The excess length is chargeable to the diffuser because all the other internal length requirements are fixed by other considerations. The difference in length is

$$L_N = L_{Lip} + L_x + L_d + 3.545\, D_2 - 5.5\, D_m \quad .$$

The change in drag is given by

$$\Delta\, \text{Drag} = C_D\, \tfrac{1}{2} \rho V_o^{\,2}\, \Delta S,$$

because C_D is essentially a constant for small changes in L_N.

The change in length can be considered to be all in a cylinderical section of diameter D_m.

$$\Delta S = \pi D_m\, \Delta L_N$$

The increase in power due to the increase in drag is

$$\Delta\, \text{Power}_1 = C_D\, \tfrac{1}{2} \rho V_o^3\, \pi D_m\, \Delta L_N \quad .$$

The power to overcome the diffuser losses is found by

$$\Delta\, \text{Power}_2 = (CK_t + fL_d/d_m) \tfrac{1}{2} \rho V_i^{\,2} Q \quad .$$

The total increase in power required to operate the diffuser is then

$$\Delta\, \text{Power} = \Delta \text{Power}_1 + \Delta\, \text{Power}_2 \quad .$$

In the subroutine, the minimum value of Δ Power is determined by iteration on L_d.

Appendix C. SUBROUTINE LISTING

SUBROUTINE NACEL and its flow diagram listed in the following pages are in the form for which the rationale is described in chapters 6 and 7. Similar listings for FUNCTION TABLE, which was not programmed by the author but was furnished for common ues with reference 1, follow NACEL. FUNCTION CFS is also shown for completeness but no flow diagram was generated for it because of its simplicity.

The FORTRAN names below, used for various variables and constants in the subroutine, are described as an aid in understanding the logic and specific calculations. The symbols are listed in approximate order of first occurance beginning with the first executable statement.

ZK -	A constant decimal less than one which indicates how much of the annulus occupied by the auxiliary inlet is available for opening.
SPO -	Static pressure in the free stream in p.s.f.
HS -	Depth of submergence in feet.
HA -	Pressure head of the atmosphere in feet of water.
RHOW -	Density of water in slugs per cubic foot.
G -	Acceleration of gravity, 32.174 feet/sec^2.
PVP -	Vapor pressure of water in p.s.f.
PV -	Vapor pressure of water in feet of water.
VELR(I) -	Inlet velocity ratio at speed I. I = 1 indicates cruise. I = 2 indicates take-off.

I greater than 2 indicates a performance evaluation speed.

VI(I) - Inlet velocity in feet/sec.

VO(I) - Free stream velocity in feet/sec.

SIGTV - Incipient cavitation number on the turning vanes referenced to diffuser exit pressure and velocity.

JNUMB - A counter.

ISTRT - A control variable indicating whether the current calculation is part of the design process (ISTRT = 1), or part of the evaluation process (ISTRT = 3).

NUMB - A control variable indicating the total number of speeds to be considered.

QO(I) - Free stream dynamic pressure at speed I in p.s.f.

SIGI(I) - Free stream incipient cavitation number.

PTO(I) - Free stream stagnation pressure in p.s.f.

TRIM(I) - Angle of attack in degrees.

CPEX - External minimum pressure coefficient.

CDUMX - A dummy array generated during interpolation.

CDUMY - A dummy array generated during interpolation.

CPEXT(J,K,I) - Tabulated minimum pressure coefficients in the external flow at the Jth velocity ratio, Kth length to diameter ratio, and Ith angle of attack.

CPINT(J,K,I) - Tabulated minimum pressure coefficients in the internal flow.

VRT - Tabulated array of velocity ratios.

IL, KL, ML, NL - Control variables indicating the order of interpolation desired.

XDT - Tabulated array of angle of attack.

XDTT(I) - A dummy array generated during interpolation.

DIDMT - Tabulated array of D_i/D_m.

DIDMX - The maximum value of D_i/D_m for a V_i/V_o as determined from interpolation in the data table.

XD - A working variable for length to diameter ratio.

WGTS(1,1) - Wet weight of the nacelle in pounds.

DIDM - Current value of D_i/D_m.

QI - Flow rate at cruise through one inlet in c.f.s.

AI - Nose inlet area in feet squared.

DI - Current value of D_i in feet.

DM - Current value of D_m in feet.

ELEXT - Length of the forebody in feet.

VRTT(I) - A dummy velocity ratio array generated during interpolation.

VRTEX(I) - A dummy velocity ratio array generated during interpolation.

VRMAX(I) - Maximum allowed velocity ratio for a given

D_i/D_m as determined from the tables.

QIN - Working variable for flow rate through the nose inlet at take-off in c.f.s.

QC - Required flow rate at take-off in c.f.s.

QAUX - Flow rate through the auxiliary inlet in c.f.s.

KDEX - A counter.

VI2 - Working variable for VI(2).

PRLT - Tabulated array of pressure recovery coefficients for the lip.

PRLT2 - Lip pressure recovery coefficient at take-off.

PTI - Stagnation pressure in the internal flow in p.s.f.

SPI - Static pressure in the internal flow in p.s.f.

AIAUX - Area of the auxiliary inlet in feet squared.

VIAUX - Auxiliary inlet velocity ratio.

PTAUX - Stagnation pressure inside the auxiliary inlet in p.s.f.

PRAUX - Pressure recovery coefficient of the auxiliary inlet.

DYP - Dynamic pressure inside the auxiliary inlet in p.s.f.

PC - Stagnation pressure in the combined flows from the auxiliary and nose inlets in p.s.f.

DLIP(I) - Inlet losses at speed I in p.s.f.

QDIF - Flow rate through the diffuser in c.f.s.

ELENT - Interior length of the lip in feet.

PHI - The angle labeled θ_x in Figure 3.

ELAUX - Interior length due to the auxiliary inlet in feet.

ELMAX - Maximum permissible length of the diffuser in feet.

ELMIN - Minimum permissible length of the diffuser in feet.

QDIF - Flow rate through the diffuser in c.f.s.

EL - Current value of the diffuser length in feet.

DEL - Change in diffuser length in feet.

ELN - Length of the nacelle in feet.

ELD, ELL - Working variables for ELN.

DDM - Mean diameter of the diffuser in feet.

XKT - Sudden expansion loss coefficient, K_t.

REL - Reynolds number based on length.

RED - Reynolds number based on diameter.

DL - Ratio, D_m/L_N.

CDRG - Drag coefficient.

ANGL - Deffuser half angle of expansion, labeled θ in Figure 3.

POW - Current value of the power charged to the diffuser in ft.lbs./sec.

POWI - Previous value of POW.

ELDIF- Final value of diffuser length in feet.

REND - Same as RED.

RENL - Same as REL.

DDIF - Diffuser loss in p.s.f.

PLOSS - Sum of diffuser, pipe and lip losses in p.s.f.

VAOUT - Average diffuser exit velocity in ft./sec.

VCRIT - Critical diffuser exit velocity at which cavitation occurs on the turning vanes in ft./sec.

VMAX - Maximum diffuser exit velocity in ft./sec.

DELH(I,1) - PLOSS converted to head in feet of water at speed I.

PRC(I) - Ram pressure recovery coefficient at the diffuser exit.

CD(I) - Drag coefficient.

AEXN - Wetted area of the nacelle in feet squared.

CPOD(I) - Drag of two nacelles in pounds.

AREA(1) - Diffuser exit area of two diffusers in feet squared.

CGS(1,1) - Distance of the vertical center of gravity of the nacelles from the keel in feet.

CGS(2,1) - Distance of the longitudinal center of gravity of the nacelles from the transom in feet.

CGS(3,1) - Distance of the VCG of the contained water from the keel in feet.

CGS(4,1) - Distance of the LCG of the contained water

from the transom in feet.

RHOD - Density of steel in slugs per cubic foot.

```
      SUBROUTINE NACEL
      COMMON /WARN/CAV(5,6)
      COMMON /TOLER/DELTA
      COMMON /H2O/TEMP,PV,RHOW,GNU,HA
      COMMON /SHIP/DISP,RANGE,BEAM,HS,HE,HCL,XLS,XLPE,XLP
      COMMON /CONST/PI,G,RHOD
      COMMON /CHARS/WGTS(2,15),CGS(4,15),DELH(5,15)
      COMMON /FLOW/Q(5),AIN,AJET,AREA(11),VJ(5),VI(5)
      COMMON /INDEX/IEVAL,IEQPT,ISTRT,NUMB,IENGN,ITYPE,ICOMP,NPUMP,NGT
      COMMON /DRAG/TDRAG(5),STRTD(5),POD(5),SPRAY(5),REST(5),VO(5),
     1 TRIM(5)
      COMMON /CDRAG/CSTRT(5),CPOD(5),CSPRY(5)
      COMMON /NACLL/DRAT,DM,ELEXT,ELENT,D1,D2,ELDIF,ELAUX, AI,AIAUX,ELN,
     1ELMIN,ELMAX
      COMMON /ELBW/XK(4),RD(4),THATA(4),WIDTH,DEPTH,TYPE(3,4)
      DIMENSION NL(2),ML(2),KL(2),JL(2),IL(2)
      DIMENSION AA(30),AB(30),AC(30),AD(30),AE(30),AF(30),AG(30),AH(30)
      DIMENSION BA(30),BB(30),BC(30),BD(30),BE(30),BF(30),BG(30),BH(30)
      DIMENSION ALFAT(4),VRT(6), XDT(10),CPINT(6,10,4),CPEXT(6,10,4),
     1PRLT(6),SIGI(5),PTO(5),XDTT(4),CDUMX(10),  CDUMY(10),  AT(2)
     2,DIDMT(10),VRTT(4),DLIP(5),         QO(5) ,VELR(5),VRTEX(4)
      EQUIVALENCE (CPINT(1,1,1),AA(1)),(CPINT(1,6,1),AB(1)),(CPINT(1,1,2
     1),AC(1)),(CPINT(1,6,2),AD(1)),(CPINT(1,1,3),AE(1)),(CPINT(1,6,3),
     2AF(1)),(CPINT(1,1,4),AG(1)),(CPINT(1,6,4),AH(1)),(CPEXT(1,1,1),BA(
     31)),(CPEXT(1,6,1),BB(1)),(CPEXT(1,1,2),BC(1)),(CPEXT(1,6,2),BD(1))
     4,(CPEXT(1,1,3),BE(1)),(CPEXT(1,6,3),BF(1)),(CPEXT(1,1,4),BG(1)),
     5(CPEXT(1,6,4),BH(1))
      EQUIVALENCE (AT(1),ALFAT(1)) ,(DIDM,DRAT)
      DATA NL,ML,KL,JL/6, 2,2*2,10,3,6,3/,IL/4,2/
      DATA PRLT/0.973,0.969,0.962,0.945,0.928,0.909/
      DATA ALFAT/0.0,2.0,4.0,6.0/,
     1 XDT/0.25,0.50,0.75,1.0,1.25,1.50,1.75,2.0,2.25,2.5/,DIDMT/0.810,
     2 0.695,0.627,0.577,0.533,0.490,0.439,0.365,0.260,0.090/
     3, VRT/.7,.8,.9,1.05,1.15,1.25/
      DATA AA/
     A  0.170  , -0.150  , -0.540  , -1.300  , -1.980  , -2.770  ,
```

```
B  0.267  ,  0.010  , -0.300  , -0.860  , -1.330  , -1.925  ,
C  0.335  ,  0.125  , -0.145  , -0.605  , -0.965  , -1.415  ,
D  0.378  ,  0.175  , -0.055  , -0.470  , -0.775  , -1.120  ,
E  0.403  ,  0.212  , -0.005  , -0.383  , -0.665  , -0.975  /
 DATA AB/
A  0.413  ,  0.233  ,  0.026  , -0.333  , -0.510  , -0.887  ,
B  0.417  ,  0.245  ,  0.053  , -0.302  , -0.506  , -0.832  ,
C  0.419  ,  0.254  ,  0.071  , -0.278  , -0.502  , -0.790  ,
D  0.420  ,  0.262  ,  0.082  , -0.259  , -0.499  , -0.752  ,
E  0.421  ,  0.271  ,  0.090  , -0.241  , -0.480  , -0.720  /
 DATA AC/
A  0.000  , -0.360  , -0.800  , -1.570  , -2.430  , -3.900  ,
B  0.157  , -0.125  , -0.475  , -1.118  , -1.680  , -2.750  ,
C  0.260  ,  0.018  , -0.258  , -0.788  , -1.075  , -1.670  ,
D  0.328  ,  0.102  , -0.130  , -0.583  , -0.930  , -1.250  ,
E  0.365  ,  0.160  , -0.060  , -0.464  , -0.770  , -1.020  /
 DATA AD/
A  0.386  ,  0.196  , -0.018  , -0.385  , -0.664  , -0.902  ,
B  0.398  ,  0.220  ,  0.011  , -0.330  , -0.595  , -0.836  ,
C  0.407  ,  0.238  ,  0.034  , -0.287  , -0.545  , -0.780  ,
D  0.414  ,  0.252  ,  0.055  , -0.258  , -0.507  , -0.766  ,
E  0.417  ,  0.263  ,  0.071  , -0.222  , -0.482  , -0.742  /
 DATA AE/
A -0.215  , -0.590  , -1.140  , -2.150  , -3.150  , -4.450  ,
B  0.020  , -0.295  , -0.700  , -1.465  , -2.185  , -3.240  ,
C  0.160  , -0.105  , -0.408  , -0.980  , -1.450  , -2.000  ,
D  0.255  ,  0.010  , -0.255  , -0.710  , -1.070  , -1.455  ,
E  0.310  ,  0.088  , -0.145  , -0.554  , -0.860  , -1.180  /
 DATA AF/
A  0.345  ,  0.152  , -0.075  , -0.450  , -0.725  , -1.024  ,
B  0.367  ,  0.200  , -0.030  , -0.383  , -0.643  , -0.930  ,
C  0.386  ,  0.225  ,  0.012  , -0.328  , -0.589  , -0.880  ,
D  0.401  ,  0.243  ,  0.048  , -0.280  , -0.541  , -0.850  ,
E  0.412  ,  0.258  ,  0.060  , -0.245  , -0.509  , -0.820  /
 DATA AG/
A -0.550  , -0.950  , -1.600  , -2.940  , -3.500  , -5.200  ,
```

```
B -0.250   , -0.570   , -1.020   , -1.900   , -2.650   , -3.920   ,
C  0.000   , -0.275   , -0.600   , -1.230   , -1.770   , -2.385   ,
D  0.150   , -0.045   , -0.340   , -0.950   , -1.365   , -1.960   ,
E  0.255   ,  0.020   , -0.200   , -0.800   , -1.215   , -1.800   /
 DATA AH/
A  0.315   ,  0.120   , -0.110   , -0.685   , -1.130   , -1.715   ,
B  0.355   ,  0.173   , -0.050   , -0.614   , -1.087   , -1.665   ,
C  0.375   ,  0.195   ,  0.000   , -0.575   , -1.060   , -1.640   ,
D  0.392   ,  0.225   ,  0.032   , -0.545   , -1.035   , -1.625   ,
E  0.405   ,  0.248   ,  0.060   , -0.520   , -1.017   , -1.617   /
 DATA BA/
A -0.485   , -0.460   , -0.450   , -0.410   , -0.400   , -0.385   ,
B -0.335   , -0.330   , -0.315   , -0.300   , -0.295   , -0.280   ,
C -0.240   , -0.239   , -0.230   , -0.225   , -0.220   , -0.215   ,
D -0.175   , -0.185   , -0.170   , -0.170   , -0.165   , -0.164   ,
E -0.140   , -0.145   , -0.135   , -0.140   , -0.135   , -0.135   /
 DATA BB/
A -0.115   , -0.120   , -0.110   , -0.115   , -0.110   , -0.115   ,
B -0.100   , -0.105   , -0.100   , -0.100   , -0.100   , -0.100   ,
C -0.093   , -0.095   , -0.095   , -0.095   , -0.092   , -0.095   ,
D -0.090   , -0.090   , -0.090   , -0.090   , -0.090   , -0.090   ,
E -0.088   , -0.088   , -0.088   , -0.088   , -0.088   , -0.085   /
 DATA BC/
A -0.540   , -0.500   , -0.490   , -0.460   , -0.410   , -0.435   ,
B -0.365   , -0.350   , -0.335   , -0.320   , -0.305   , -0.305   ,
C -0.270   , -0.265   , -0.245   , -0.235   , -0.230   , -0.230   ,
D -0.205   , -0.205   , -0.185   , -0.175   , -0.175   , -0.180   ,
E -0.165   , -0.160   , -0.145   , -0.140   , -0.140   , -0.145   /
 DATA BD/
A -0.140   , -0.130   , -0.120   , -0.115   , -0.115   , -0.120   ,
B -0.125   , -0.110   , -0.105   , -0.100   , -0.100   , -0.105   ,
C -0.115   , -0.095   , -0.095   , -0.095   , -0.092   , -0.095   ,
D -0.110   , -0.090   , -0.090   , -0.090   , -0.090   , -0.090   ,
E -0.105   , -0.085   , -0.085   , -0.085   , -0.088   , -0.085   /
 DATA BE/
A -0.595   , -0.535   , -0.535   , -0.460   , -0.445   , -0.445   ,
```

```
      B -0.420  , -0.390  , -0.370  , -0.350  , -0.335  , -0.330  ,
      C -0.330  , -0.310  , -0.275  , -0.260  , -0.260  , -0.260  ,
      D -0.275  , -0.265  , -0.215  , -0.205  , -0.205  , -0.195  ,
      E -0.250  , -0.230  , -0.175  , -0.165  , -0.165  , -0.160  /
       DATA BF/
      A -0.235  , -0.205  , -0.145  , -0.145  , -0.140  , -0.138  ,
      B -0.235  , -0.185  , -0.135  , -0.130  , -0.125  , -0.125  ,
      C -0.240  , -0.170  , -0.125  , -0.120  , -0.118  , -0.118  ,
      D -0.250  , -0.155  , -0.120  , -0.115  , -0.115  , -0.113  ,
      E -0.265  , -0.145  , -0.118  , -0.112  , -0.114  , -0.110  /
       DATA BG/
      A -0.670  , -0.610  , -0.570  , -0.525  , -0.475  , -0.480  ,
      B -0.485  , -0.460  , -0.415  , -0.380  , -0.365  , -0.360  ,
      C -0.395  , -0.373  , -0.335  , -0.293  , -0.285  , -0.280  ,
      D -0.348  , -0.322  , -0.285  , -0.235  , -0.232  , -0.225  ,
      E -0.331  , -0.300  , -0.255  , -0.200  , -0.195  , -0.190  /
       DATA BH/
      A -0.337  , -0.295  , -0.238  , -0.176  , -0.171  , -0.168  ,
      B -0.360  , -0.300  , -0.231  , -0.163  , -0.157  , -0.154  ,
      C -0.400  , -0.310  , -0.230  , -0.157  , -0.150  , -0.145  ,
      D -0.447  , -0.323  , -0.229  , -0.155  , -0.146  , -0.139  ,
      E -0.499  , -0.336  , -0.230  , -0.153  , -0.144  , -0.135  /
       FRICT(RE)=(.86859*ALOG(RE/(1.964*ALOG(RE)-3.8215)))**(-2)
C
C        ZK   IS THE DECIMAL PART OF THE ANNULUS OCCUPIED BY THE
C        AUXILIARY INLET THAT IS ACTUALLY OPENING.  THE REMAINDER IS
C        STRUCTURE.
C
       ZK=.8
       SPO=(HS+HA)*RHOW*G
       PVP=PV*RHOW*G
       VELR(1)=VI(1)/VO(1)
C
C        SIGTV  IS THE INCIPIENT CAVITATION NO. ON THE ELBOW TURNING
C        VANES REFERENCED TO DIFFUSER EXIT PRESSURE AND VELOCITY.
C
```

```
      SIGTV=0.4
      JNUMB=2
C
C      NUMB  IS AN INDEX INDICATING THE TOTAL NO. OF SPEEDS TO BE
C      EXAMINED.
C         NUMB=2 IF ONLY CRUISE AND TAKE-OFF ARE SPECIFIED.
C         NUMB=3 OR MORE IF ONE OR MORE OFF-DESIGN SPEEDS ARE SPECIFIED.
C
C      ISTRT  IS AN INDEX INDICATING WHETHER THE CURRENT OPERATION IS
C      PART OF THE DESIGN PROCESS, IN WHICH ITS VALUE IS 1, OR PART OF
C      THE EVALUATION PROCESS, IN WHICH CASE ITS VALUE IS 3 .
C
      IF(ISTRT.EQ.3)JNUMB=NUMB
      DO 10 I=ISTRT,JNUMB
      QO(I)=.5*RHOW*VO(I)*VO(I)
C
C      SIGI(I) IS THE INCIPIENT CAVITATION NO. REFERENCED TO FREE STREAM
C      CONDITIONS.
C
      SIGI(I)=(SPO-PVP)/QO(I)
      PTO(I)=SPO+QO(I)
   10 CONTINUE
      IF(TRIM(1).GT.3.)TRIM(1)=3.
      CPEX=-SIGI(1)
C
C      INTERPOLATE IN THE DATA TABLE TO FIND THE INLET WITH THE DESIRED
C      PRESSURE COEFFICIENT.
C
      DO 610 I=1,2
      DO 609 K=1,10
      DO 608 J=1,6
      CDUMX(J)=CPEXT(J,K,I)
  608 CONTINUE
      CDUMY(K)=TABLE(VRT,CDUMX,VELR(1),NL)
  609 CONTINUE
      XDTT(I)=TABLE(CDUMY,XDT,CPEX,KL)
```

```
  610 CONTINUE
      ML(1)=2
      XD=TABLE(AT,XDTT,TRIM(1),ML)
      DIDMX=TABLE(XDT,DIDMT,XD,KL)
C
C       IF THE TRIAL NACELLE HAS LESS FRONTAL AREA THAN THE MINIMUM
C       REQUIRED TO AVOID CAVITATION, REJECT THE TRIAL VALUE.  IF NON-
C       CAVITATING, CALCULATE INLET DIMENSIONS.
C
      WGTS(1,1)=1.E10
      IF(DIDMX.LT.DIDM*(1.+DELTA).AND.DELTA.GT.1.E-9)RETURN
      QI=.5*Q(1)
      AI=QI/VI(1)
      DI=SQRT(AI)*1.12838
      DM=DI/DIDM
      XD=TABLE(DIDMT,XDT,DIDM,KL)
      ELEXT=DM*XD
      CPIN=-SIGI(2)
C
C       INTERPOLATE IN THE DATA TABLE TO DETERMINE THE MAXIMIM VELOCITY
C       RATIOS AT CRUISE AND TAKE-OFF.
C
      DO 710 I=1,4
      DO 709 K=1,6
      DO 708 J=1,10
      CDUMX(J)=CPINT(K,J,I)
  708 CONTINUE
      CDUMY(K)=TABLE(XDT,CDUMX,XD,KL)
  709 CONTINUE
      VRTT(I)=TABLE(CDUMY,VRT,CPIN,IL)
      VRTEX(I)=TABLE(CDUMY,VRT,CPEX,IL)
  710 CONTINUE
      ML(1)=4
      VRMAX(1)=TABLE(ALFAT,VRTEX,TRIM(1),ML)
      VRMAX(2)=TABLE(ALFAT,VRTT,TRIM(2),ML)
C
```

```
C      CHECK FOR LIP CAVITATION AT CRUISE.  IF CAVITATING, REJECT.
C
      IF(VELR(1).GT.VRMAX(1).AND.DELTA.GT.1.E-9)RETURN
C
C      DETERMINE MAX. FLOW RATE AT TAKE-OFF AND COMPARE WITH REQUIRED
C      FLOW RATE.  AN AUXILIARY INLET MUST BE SIZED TO ACCEPT ANY EXCESS
C      REQUIRED FLOW.
C
      QIN=AI*VRMAX(2)*VO(2)
C
C     ASSUMING THE AUX. INLETS ALLOW FLOW TO ENTER BEFORE THE DIFFUSER,
C     CALCULATE LOSSES AND TOTAL PRESSURE OF THE COMBINED FLOW.
C
      QC=0.5*Q(2)
      QAUX=QC-QIN
      IF(QAUX.LE.0.)QAUX=0.
      QIN=QC-QAUX
      KDEX=0
C     CALCULATE STATIC PRESSURE IMMEDIATELY AFT. OF THE LIP.
      VI2=QIN/AI
      VR=VI2/VO(2)
      PRL2=TABLE(VRT,PRLT,VR,JL)
      PTI=PRL2*QO(2)+SPO
      SPI=PTI-0.5*RHOW*VI2*VI2
C     CALCULATE COMBINED FLOW PRESSURES AND AUX. INLET AREA.
      AIAUX=0.
      VIAUX=0.
      PTAUX=0.
      IF(QAUX.EQ.0.)GO TO 12
      PRAUX=0.80
      PTAUX=PRAUX*QO(2)+SPO
      DYP=PTAUX-SPI
      VIAUX=SQRT(2.*DYP/RHOW)
      AIAUX=QAUX/VIAUX
C
C      THE TOTAL PRESSURE OF THE COMBINED FLOW IS CALCULATED AS THE
```

```
C        MASS WEIGHTED AVERAGE OF THE COMBINING FLOWS.
C
   12 CONTINUE
      PC=(PTI*QIN+PTAUX*QAUX)/QC
      VI(2)=SQRT(2.*(PC-SPI)/RHOW)
      DLIP(2)=1.-(PC-SPO)/QO(2)
      QDIF=QC
C
C        CALCULATE THE INTERNAL LENGTHS TO THE DIFFUSER ENTRY.
C
      ELENT=ELEXT/9.
      PHI=ATAN(.5*(DM-DI)/ELEXT)
      PHS=SIN(PHI)
      X=.5*(SQRT(DI**2+1.27324*AIAUX*PHS/ZK)-DI)/PHS
      ELAUX=X/COS(PHI)
C     SIZE THE DIFFUSER
      D2=C.9*DM
      D1=DI
      IF(D2.LT.D1)D2=D1
      ELMAX=9.22339*(D2-D1)
      ELMIN=2.836075*(D2-D1)
C
C     DECIDE WHICH CONDITION GOVERNS THE DIFFUSER.
C
      IF(QI.GT.QC)GO TO 13
      II=2
      GO TO 14
   13 CONTINUE
      II=1
      QDIF=QI
   14 CONTINUE
      EL=C.5*(ELMAX+ELMIN)
      DEL=0.
  111 EL=EL+DEL
      KDEX=KDEX+1
      IF(KDEX.GT.10)GO TO 112
```

```
      ELD=ELENT+EL+3.5491*D2+ELAUX
      ELL=5.5*DM
      ELN=ELD
      IF(ELL.GE.ELD)ELN=ELL
      ELFAC=(ELD-ELL)
      DDM=0.5*(D2+D1)
      XKT=(1.-(D1/D2)**2)**2
      IF(ELFAC.LE.0.)ELFAC=0.
      REL=VO(II)*ELN/GNU
      RED=VI(II)*D1/GNU
      DL=DM/ELN
      CDRG =CFS(REL)*(1.+1.5*DL**(3/2)+7.*DL**3)
      ANGL=0.
      IF(EL.LT.0.001)GO TO 109
      ANGL=ATAN((D2-D1)/(2.*EL    ))*57.2958
  109 CDIF=3.19E-3*ANGL*ANGL+8.452E-4*ANGL
      POW=CDRG*DM*.5*PI*RHOW*VO(II)**3*ELFAC+(CDIF*XKT+FRICT(RED)*EL/DDM
     1)*.5*RHOW*VI(II)*VI(II)*QDIF
      DEL=.1*(ELMAX-ELMIN)
      IF(KDEX.EQ.1)GO TO 110
      DEL=(POWI-POW)*EL/POWI
  110 POWI=POW
      IF(DEL.LE.0.01*EL)GO TO 112
      GO TO 111
C
C      ELDIF  IS THE DIFFUSER LENGTH REQUIRING THE LEAST TOTAL POWER
C      FOR THE DESIRED  DIFFUSION RATIO.
C
  112 ELDIF=EL
C
C      CALCULATE THE LIP LOSSES FOR EACH SITUATION.
C
      DLIP(1)=1.-TABLE(VRT ,PRLT,VELR(1),JL)
      IF(NUMB.LT.3)GO TO 113
      DO 15 J=3,NUMB
      VI(J)=.5*Q(J)/AI
```

```
      VELR(J)=VI(J)/VO(J)
      DLIP(J)=1.-TABLE(VRT,PRLT,VELR(J),JL)
   15 CONTINUE
  113 JNUMB=2
      IF(ISTRT.EQ.3)JNUMB=NUMB
      DO 17 I=ISTRT,JNUMB
      CAV(I,3)=0.
C
C      CALCULATE THE DIFFUSER AND PIPE LOSSES FOR EACH SITUATION AND
C      ADD TO THE LIP LOSSES.
C
      REND=D1*VI(I)/GNU
      DDIF=(CDIF*XKT+FRICT(REND)*ELDIF/DDM)*0.5*RHOW*VI(I)*VI(I)
      PLOSS=DLIP(I)*QO(I)+DDIF+FRICT(REND)*ELAUX/DI*.5*RHOW*VI(1)*VI(1)
      IF(I.EQ.2)PLOSS=DLIP(2)*QO(2)+DDIF
      VAOUT=Q(I)*0.63662/(D2*D2)
      SQUAR=SIGI(I)+1.-PLOSS/QO(I)
C
C      DETERMINE THE CRITICAL LOCAL VELOCITY AT THE DIFFUSER EXIT AT
C      WHICH CAVITATION ON THE TURNING VANES OCCURS.
C
      VCRIT=SQRT(SQUAR)*VO(I)/SQRT(1.+SIGTV)
C
C      ESTIMATE THE MAXIMUM LOCAL VELOCITY AT THE DIFFUSER EXIT.
C
      VMAX=1.50*VAOUT
C
C      IF CAVITATION OCCURS, REJECT ON DESIGN, INDICATE ON EVALUATION.
C
      IF(VMAX.GT.VCRIT.AND.ISTRT.EQ.1.AND.DELTA.GT.1.E-9)RETURN
      IF(VMAX.GT.VCRIT)CAV(I,3)=1.
C     AT THIS POINT THE DIFFUSER HAS BEEN SIZED TO AVOID CAVITATION AT
C      BOTH TAKE/OFF AND CRUISE. INTERNAL FLOW LOSSES ARE DETERMINED
C
      DELH(I,1)=PLOSS/(RHOW*G)
C      THE FOLLOWING CARD IS USED ONLY WITH A TEST PROGRAM.
```

```
      PRC(I)=(PTO(I)-PLOSS-SPO)/QO(I)
C
C      CALCULATE THE DRAG COEFFICIENTS.
C
      RENL=ELN*VO(I)/GNU
      CD(I)=CFS(RENL)*(1.+1.5*(DM/ELN)**(3/2)+7.*(DM/ELN)**3)
C
C     CALCULATE WETTED SURFACE AND DRAG.
C
      EM=SQRT(1.+4.*((2.*ELEXT)/DM)**2)
      AEXN=1.0472*DM*DM*(EM+1./(EM+1.))
      AEXN=AEXN+PI*DM*(ELN-2.*ELEXT)
      CPOD(I)=2.*QO(I)*AEXN*CD(I)
   17 CONTINUE
      AREA(1)=PI*D2*D2*0.5
      CGS(1,1)=HS+HE-HCL
      CGS(2,1)=XLS+.5*(ELN-3.54491*D2)
      IF(THATA(1).GE.90.)GO TO 18
      PHI=THATA(1)/57.2958
      CGS(2,1)=CGS(2,1)+CGS(1,1)/TAN(PHI)
   18 CGS(3,1)=0.
      CGS(4,1)=0.
      WGTS(1,1)=.11*DM*AEXN*(.5*RHOD-RHOW)+15.07*AREA(1)*(ELENT+ELAUX+EL
     1)
      RETURN
      END
```

CHART TITLE - SUBROUTINE NACEL

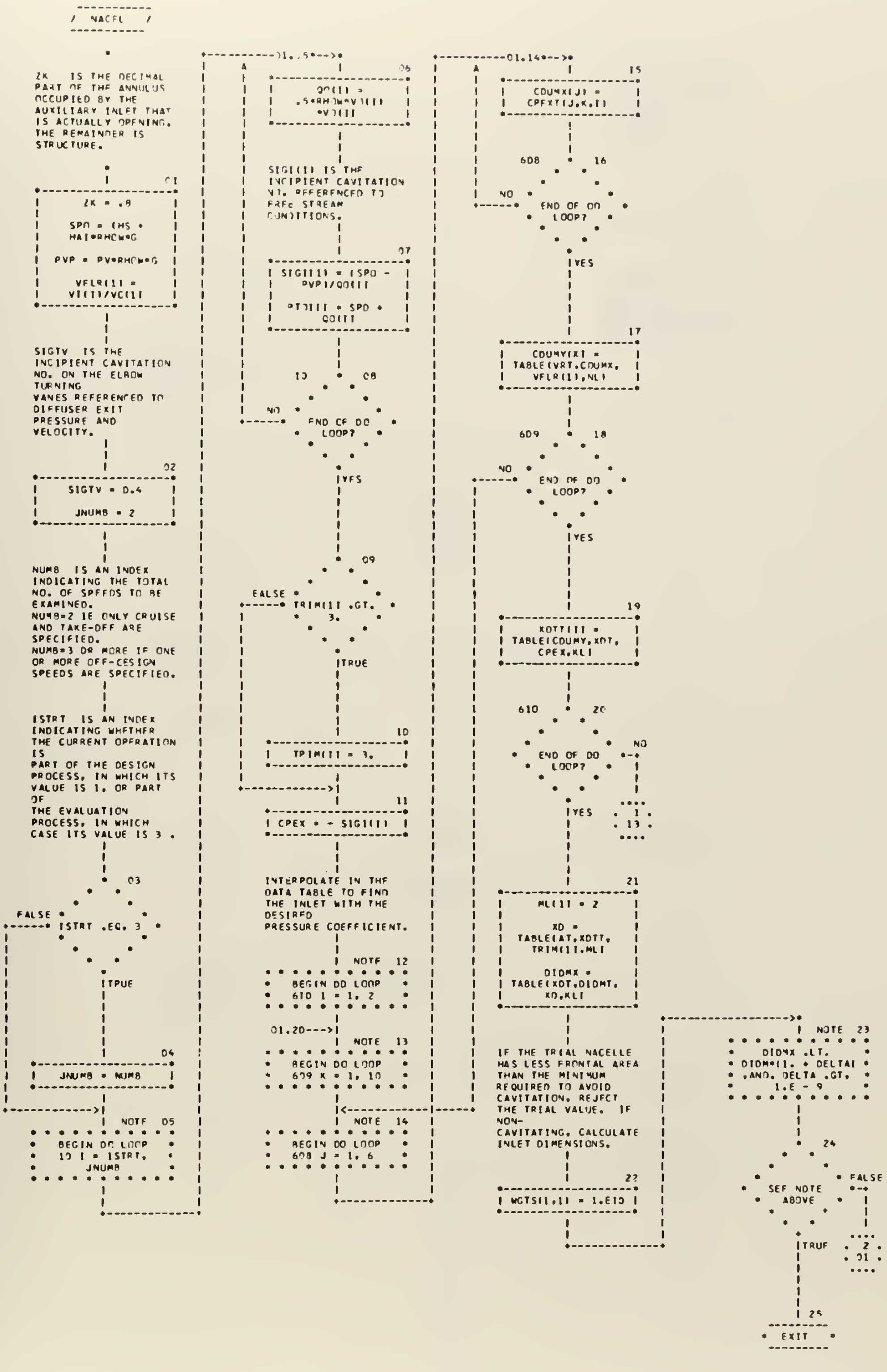


CHART TITLE - SUBROUTINE NACEI

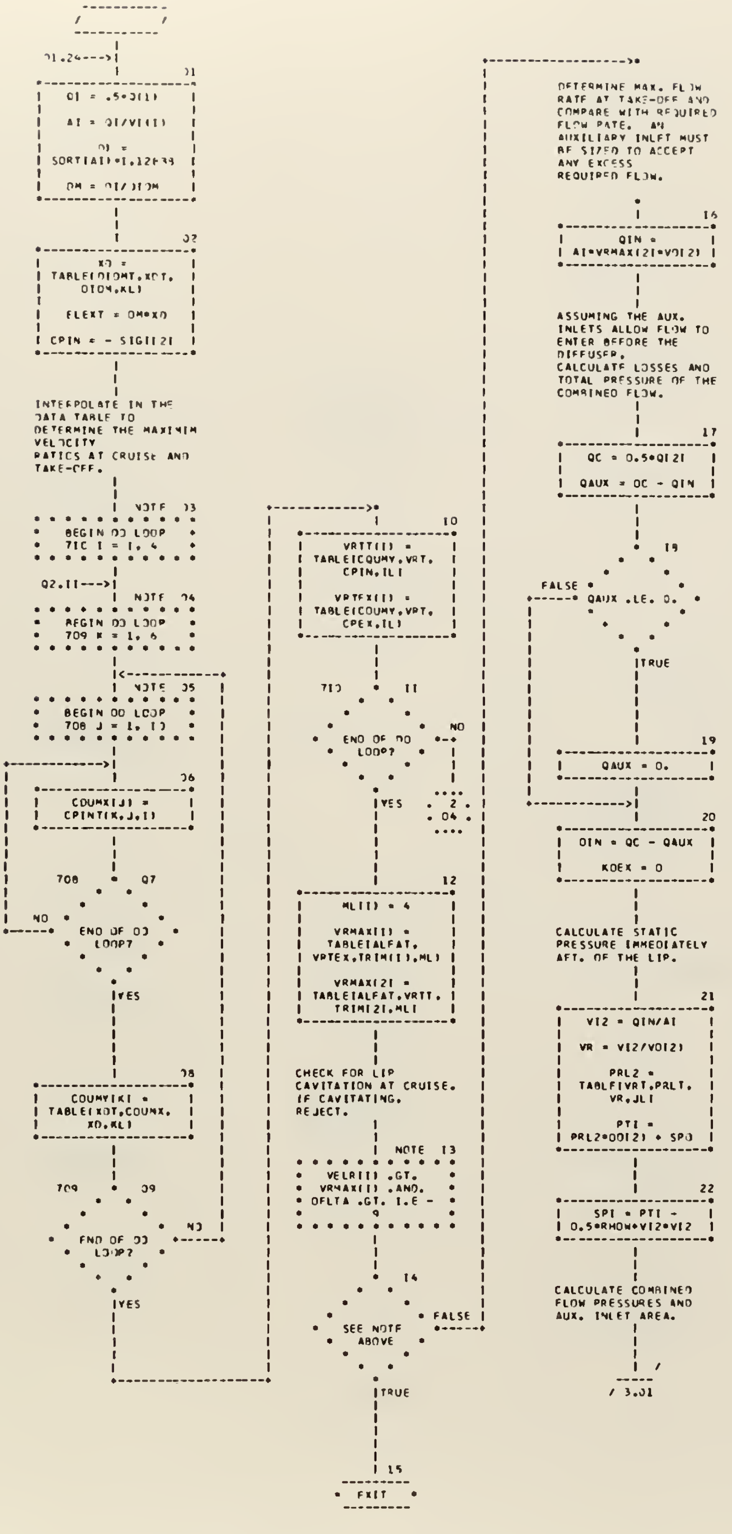


CHART TITLE - SUBROUTINE NACEL

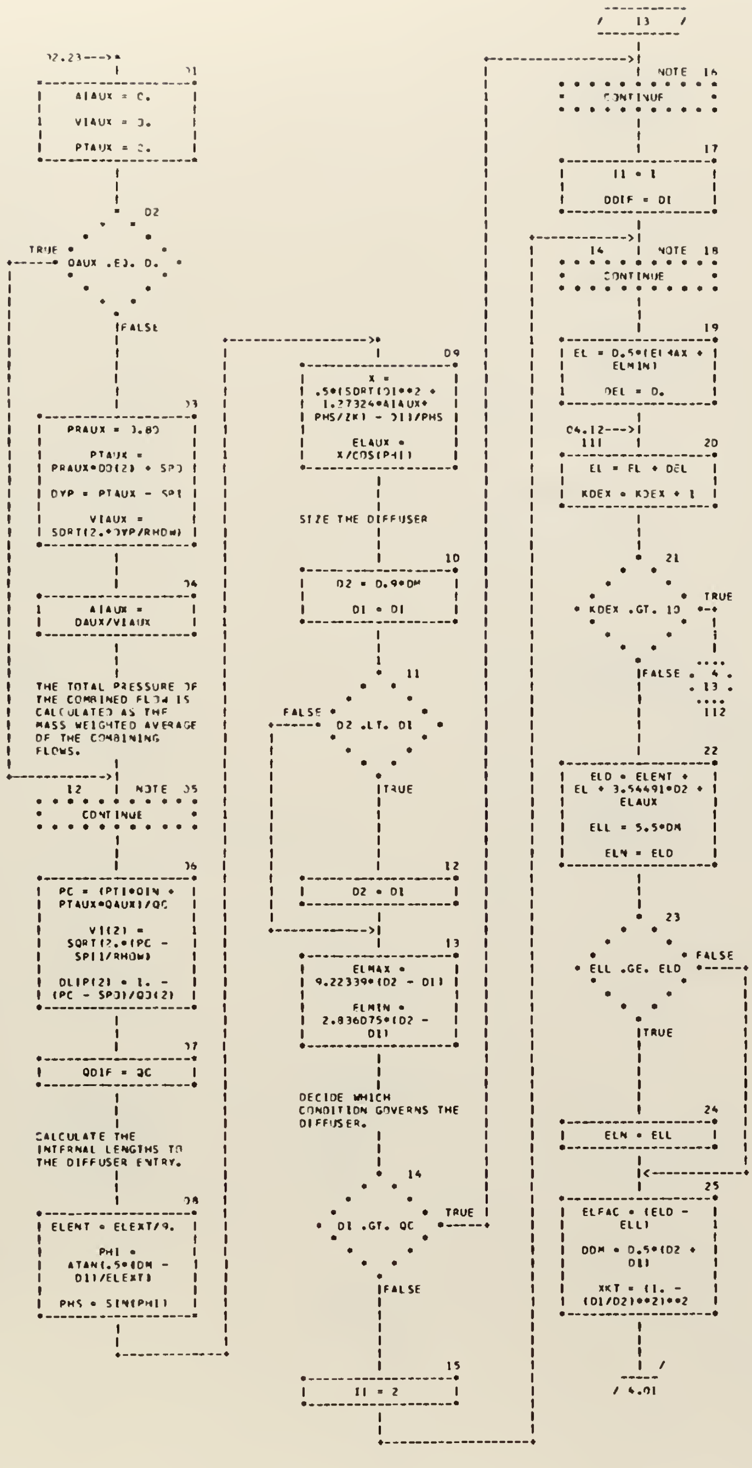


CHART TITLE - SUBROUTINE NACEL

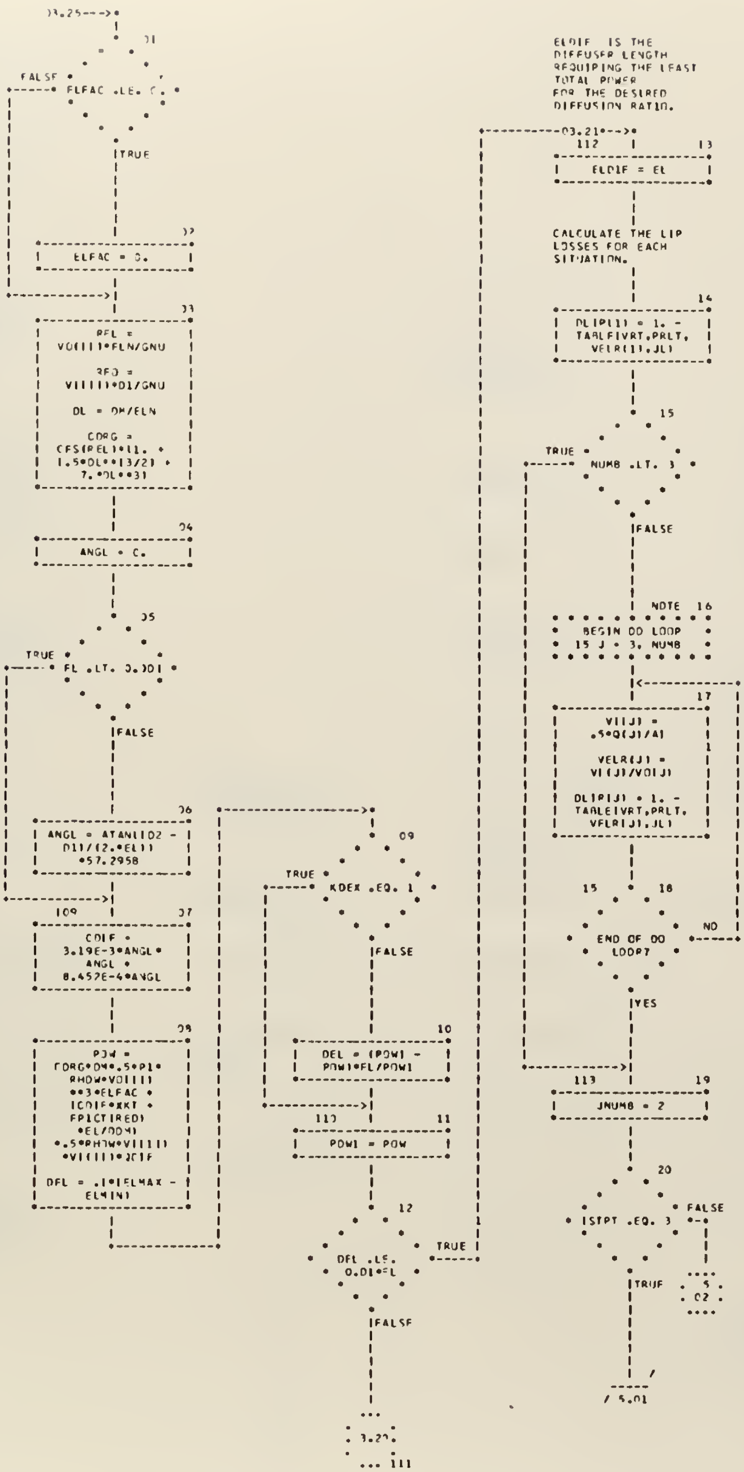


CHART TITLE - SUBROUTINE NACEL

```
04.20--->    C1
 JNUMB = NUMB

04.20--->    NOTE 02
 BEGIN DO LOOP
 17 I = ISTRT,
 JNUMB

05.22--->    03
 CAV(I,3) = 0.

CALCULATE THE
DIFFUSER AND PIPE
LOSSES FOR EACH
SITUATION AND
ADD TO THE LIP
LOSSES.
             04
 REND =
 DI*VI(I)/GNU

 DDIF =
 (CDIF*XKT +
 FRICT(REND)
 *ELDIF/DOM)
 *0.5*RHOW*VI(I)
 *V(I)
             05
 PLOSS =
 OLIP(I)*QD(I) +
 DDIF *
 FRICT(REND)
 *ELAUX/DI*.5*
 RHOW*VI(I)*VI(I)

             06
FALSE   I .EQ. 2
        TRUE
             07
 PLOSS =
 OLIP(2)*QD(2) +
 DDIF
             08
 VAOUT =
 D(I)
 *0.63662/(D2*D2)

 SQUAR = SIG(I) +
 1. - PLOSS/QD(I)

DETERMINE THE
CRITICAL LOCAL
VELOCITY AT THE
DIFFUSER EXIT AT
WHICH CAVITATION ON
THE TURNING VANES
OCCURS.

             10
 VCRIT =
 SQRT(SQUAR)*VO(I)
 /SQRT(1. + SIGTV)

ESTIMATE THE MAXIMUM
LOCAL VELOCITY AT THE
DIFFUSER EXIT.
             11
 VMAX = 1.50*VAOUT

IF CAVITATION OCCURS,
REJECT ON DESIGN,
INDICATE ON
EVALUATION.
             NOTE 12
 VMAX .GT. VCRIT
 .AND. (STRT .EQ.
 1 .AND. DELTA
 .GT. 1.E - 7

             13
 SEE NOTE        FALSE
 ABOVE
 TRUE
             14
 EXIT

             15
FALSE   VMAX .GT.
        VCRIT
        TRUE
             16
 CAV(I,3) = 1.

AT THIS POINT THE
DIFFUSER HAS BEEN
SIZED TO AVOID
CAVITATION AT
BOTH TAKE/OFF AND
CRUISE. INTERNAL FLOW
LOSSES ARE DETERMINED
             17
 DELH(I,1) =
 PLOSS/(RHOW*G)

THE FOLLOWING CARD IS
USED ONLY WITH A TEST
PROGRAM.
             18
 PRC(I) =
 (PTO(I) - PLOSS -
 SPO)/QD(I)

CALCULATE THE DRAG
COEFFICIENTS.
             19
 RENL =
 ELN*VO(I)/GNU

 CD(I) =
 CFS(RENL)*((. +
 1.5*(DM/ELN)
 **(3/2) +
 7.*(DM/ELN)**3)

CALCULATE WETTED
SURFACE AND DRAG.
             20
 EM = SQRT(1. +
 4.*((2.*ELEXT)
 /DM)**2)

 AEXN =
 (.0472*DM*DM*(EM
 + (./(EM + 1.)(
             21
 AEXN = AEXN +
 PI*DM*(ELN -
 2.*ELEXT)

 CPOD(I) =
 2.*DD(I(
 *AEXN*CD(I)

17           22
 END OF DO        NO   5
 LOOP?                 03
 YES
             23
 AREA(I) =
 PI*D2*D2*0.5

 CGS(1,1) = HS +
 HE - HCL

 CGS(2,1) = XLS +
 .5*(ELN -
 3.54491*D2)

             24
TRUE   THATA(I) .GE.
       90.
       FALSE
             25
 PHI =
 THATA(I)/57.2958

 CGS(2,1) =
 CGS(2,1) +
 CGS(1,(I/TAN(PHI)

18           26
 CGS(3,1) = 0.

 CGS(4,1) = 0.
             27
 WGTS(1,1) =
 .(I*DM*AEXN*(.5*
 RHOD - RHOW) +
 15.07*AREA(I)
 *(ELENT + ELAUX +
 FL)
             28
 EXIT
```

```
      FUNCTION TABLE(XTAB,YTAB,XIN,L)
      DIMENSION XTAB(2),YTAB(2),X(5),Y(5),A(5),B(5),L(2)
C
C     L(1)     - NUMBER OF PAIRS OF DATA POINTS ENTERED
C     L(2)     - DEGREE OF FIT, MAXIMUM IS FOUR
C     XTAB     - DATA ARRAY OF X VALUES
C     YTAB     - DATA ARRAY OF Y VALUES
C     XIN      - INDEPENDENT VARIABLE
C     TABLE    - DEPENDENT VARIABLE CORRESPONDING TO XIN
C
      NPTS=L(1)
      K=L(2)+1
      IF(K.GT.NPTS) K=NPTS
C
C     BRANCH TO TEN IF X IS INCREASING
C     BRANCH TO 160 IF X IS DECREASING
C     IF XTAB(1).EQ.XTAB(2) ABORT RUN
C
      IF(XTAB(1)-XTAB(2)) 10,290,160
   10 IF(XTAB(1)-XIN) 20,140,200
   20 DO 120 IX=2,NPTS
C
C     FIND XTAB VALUES BRACKETING XIN
C
      IF(XTAB(IX).LE.XTAB(IX-1)) GO TO 290
      IF(XTAB(IX)-XIN) 120,150,40
  120 CONTINUE
      GO TO 130
   40 CONTINUE
C
C     IF XIN LIES BETWEEN EITHER END POINT OF THE XTAB ARRAY AND ITS ADJACENT
C     POINT, THE INTERPOLATION IS LIMITED TO A SECOND DEGREE FIT
C
      IF(IX.GT.2) GO TO 60
      IF(K.GT.3) K=3
   60 IF(IX.LT.NPTS) GO TO 80
```

```
      IF(K.GT.3) K=3
   80 NDX=IX-K/2
      IF(IX.LT.NPTS) GO TO 100
      NDX=NPTS-K+1
  100 DO 110 IL=1,K
C
C     XTAB  AND YTAB VALUES FOR THE XTAB VALUES BRACKETING XIN ARE TRANSFERRED
C     TO THE LAGRANGIAN EQUATION
C
      X(IL)=XTAB(NDX)
      Y(IL)=YTAB(NDX)
      NDX=NDX+1
  110 CONTINUE
      GO TO 210
  130 CONTINUE
C
C     TO GET PAST STATEMENT NUMBER 120, XIN IS LARGER THAN THE LARGEST VALUE
C     OF X IN XTAB. EXTRAPOLATION IS NECESSARY TO FIND TABLE AT XIN
C
      TABLE=((YTAB(NPTS)-YTAB(NPTS-1))/(XTAB(NPTS)-XTAB(NPTS-1)))*
     1 (XIN-XTAB(NPTS))+YTAB(NPTS)
      RETURN
  140 IX=1
  150 TABLE=YTAB(IX)
      RETURN
  160 IF(XIN-XTAB(1)) 170,140,200
  170 DO 190 IX=2,NPTS
C
C     XTAB IS SEARCHED TO FIND THE VALUE CLOSEST TO XIN
C
      IF(XTAB(IX).GE.XTAB(IX-1)) GO TO 220
      IF(XIN-XTAB(IX)) 190,150,40
  190 CONTINUE
      GO TO 130
C
C     TO GO TO STATEMENT NUMBER 130 INDICATES XIN IS SMALLER THAN THE SMALLEST
```

```
C       VALUE OF X IN XTAB AND EXTRAPOLATION IS NECESSARY TO FIND TABLE FOR XIN
C
  200 TABLE=((YTAB(2)-YTAB(1))/(XTAB(2)-XTAB(1)))*(XIN-XTAB(1))+YTAB(1)
      RETURN
  210 DO 220 LL=1,K
      A(LL)=1.
  220 B(LL)=1.
      P=0.
C
C       PERFORM LAGRANGIAN INTERPOLATION
C
      DO 280 N=1,K
      DO 270 J=1,K
      AA=XIN-X(J)
      IF(J.EQ.N) GO TO 240
      A(N)=A(N)*AA
  240 BB=X(N)-X(J)
      IF(BB.EQ.0.) GO TO 270
      B(N)=B(N)*BB
  270 CONTINUE
      C=A(N)/B(N)*Y(N)
  280 P=P+C
      TABLE=P
      RETURN
C
C       EQUAL CONSECUTIVE OR NON-MONOTONIC VALUES OF X ENCOUNTERED IN XTAB
C
  290 TABLE=1.E30
      RETURN
      END
```

CHART TITLE - FUNCTION TABLE(XTAB,YTAB,XIN,L)

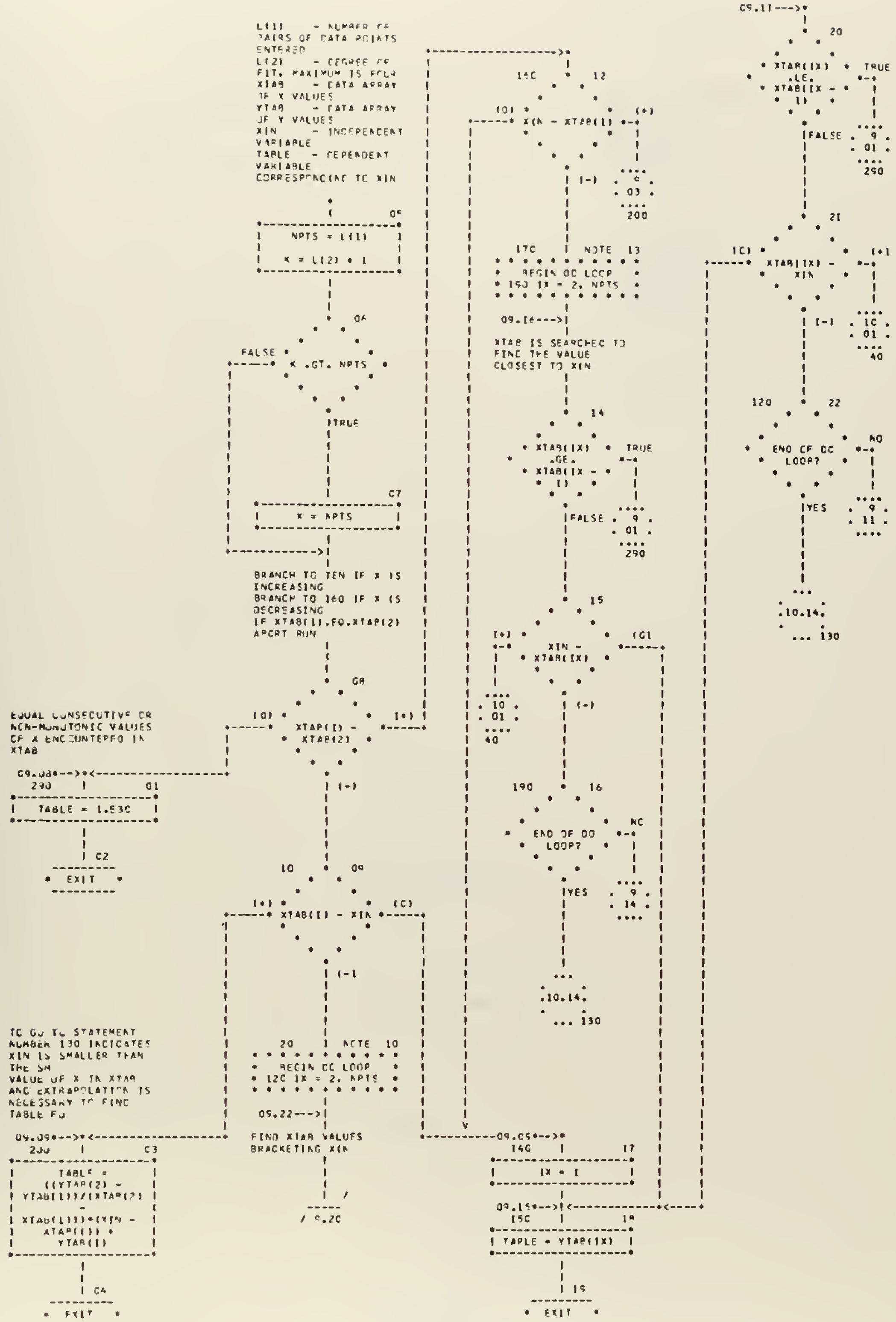


CHART TITLE - FUNCTION TABLE(XTAB,YTAB,XIN,L)

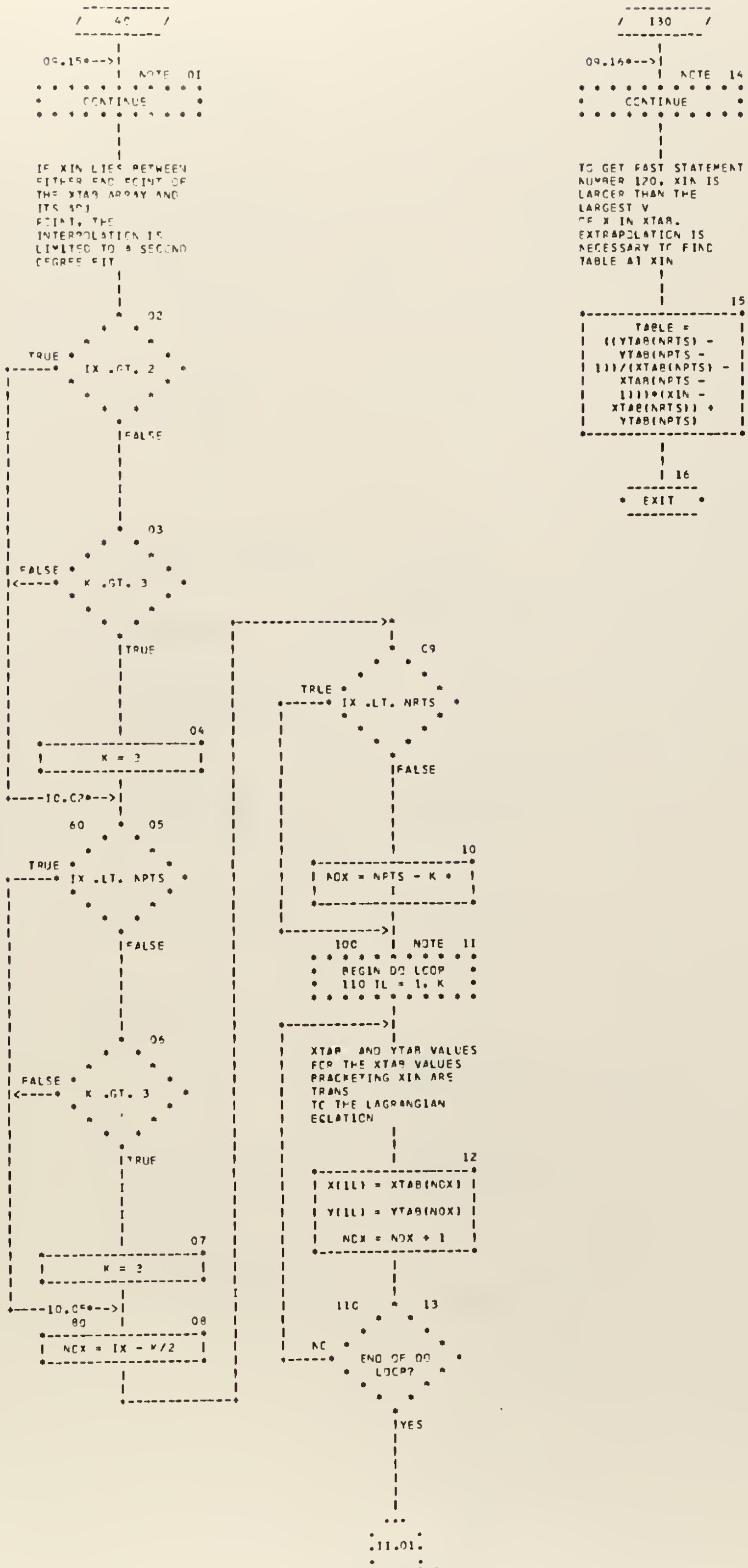
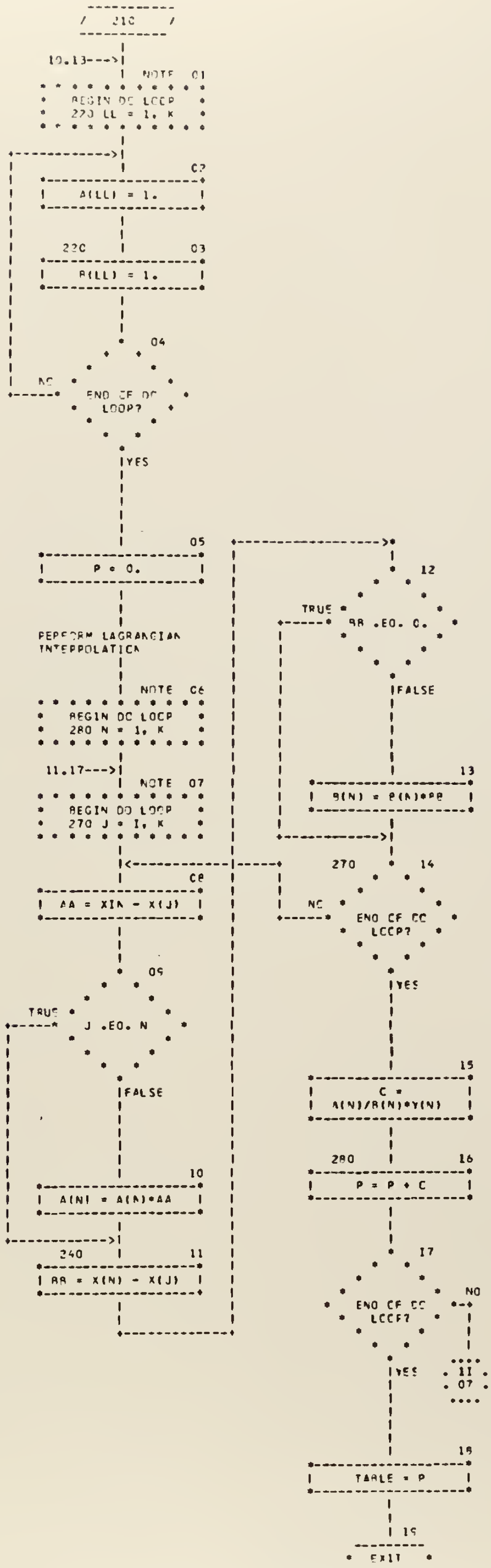


CHART TITLE - FUNCTION TABLE(XTAB,YTAB,XIN,L)



```
      FUNCTION CFS(R)
      CFS=0.004
    1 DCFS=(0.242/ALOG10(R*CFS))**2-CFS
      CFS=CFS+DCFS
      IF(DCFS.GT.1.E-6) GO TO 1
      RETURN
      END
```

Appendix D. ALTERNATE DESIGN RATIONALE USING ONLY VELOCITY RATIO AS A SYSTEM PARAMETER

Another approach to the design of the inlet nacelle can be made using the maximum allowable D_i/D_m at a given V_i/V_o in stead of allowing it to vary as a parameter. The design proceeds as previously described except that the diameter ratio determined from interpolation in the data table is used to calculate the nacelle geometry. If, after the diffuser is sized, the exit velocity is too high, then instead of rejecting that set of parameters, a new value of D_m based on the maximum allowed exit velocity is calculated and the subroutine goes back to the beginning of the design phase where a new design begins with this value.

Performance evaluation proceeds exactly as before.

The following pages contain a listing of the subroutine in this form with a flow diagram.

```
      SUBROUTINE NACEL
      COMMON /VEL/VR
      COMMON /WARN/CAV(5,6)
      COMMON /RPRC/PPC(5),CD(5),AEXN,DIDMX,VRMAX(5)
      COMMON /TOLER/DELTA
      COMMON /H2O/TEMP,PV,RHOW,GNU,HA
      COMMON /SHIP/DISP,RANGE,BEAM,HS,HE,HCL,XLS,XLPE,XLP
      COMMON /CONST/PI,G,RHOD
      COMMON /CHARS/WGTS(2,15),CGS(4,15),DELH(5,15)
      COMMON /FLOW/Q(5),AIN,AJET,AREA(11),VJ(5),VI(5)
      COMMON /INDEX/IEVAL,IEQPT,ISTRT,NUMB,IENGN,ITYPE,ICOMP,NPUMP,NGT
      COMMON /DRAG/TDRAG(5),STRTD(5),POD(5),SPRAY(5),REST(5),VO(5),
     1 TRIM(5)
      COMMON /CDRAG/CSTRT(5),CPOD(5),CSPRAY(5)
      COMMON /NACLL/DRAT,DM,ELEXT,ELENT,D1,D2,ELDIF,ELAUX, AI,AIAUX,ELN,
     1ELMIN,ELMAX
      COMMON /ELBW/XK(4),RO(4),THATA(4),WIDTH,DEPTH,TYPE(3,4)
      DIMENSION NL(2),ML(2),KL(2),JL(2),IL(2)
      DIMENSION AA(30),AB(30),AC(30),AD(30),AE(30),AF(30),AG(30),AH(30)
      DIMENSION BA(30),BB(30),BC(30),BD(30),BE(30),BF(30),BG(30),BH(30)
      DIMENSION ALFAT(4),VRT(6), XDT(10),CPINT(6,10,4),CPEXT(6,10,4),
     1PRLT(6),SIGI(5),PTO(5),XDTT(4),CDUMX(10),  CDUMY(10),  AT(2)
     2,DIDMT(10),VRTT(4),DLIP(5),        QO(5) ,VELR(5),VRTEX(4)
      EQUIVALENCE (CPINT(1,1,1),AA(1)),(CPINT(1,6,1),AB(1)),(CPINT(1,1,2
     1),AC(1)),(CPINT(1,6,2),AD(1)),(CPINT(1,1,3),AE(1)),(CPINT(1,6,3),
     2AF(1)),(CPINT(1,1,4),AG(1)),(CPINT(1,6,4),AH(1)),(CPEXT(1,1,1),BA(
     31)),(CPEXT(1,6,1),BB(1)),(CPEXT(1,1,2),BC(1)),(CPEXT(1,6,2),BD(1))
     4,(CPEXT(1,1,3),BE(1)),(CPEXT(1,6,3),BF(1)),(CPEXT(1,1,4),BG(1)),
     5(CPEXT(1,6,4),BH(1))
      EQUIVALENCE (AT(1),ALFAT(1)) ,(DIDM,DRAT)
      DATA NL,ML,KL,JL/6, 2,2*2,10,3,6,3/,IL/4,2/
      DATA PPLT/0.973,0.969,0.962,0.945,0.928,0.909/
      DATA ALFAT/0.0,2.0,4.0,6.0/,
     1 XDT/0.25,0.50,0.75,1.0,1.25,1.50,1.75,2.0,2.25,2.5/,DIDMT/0.810,
     2 0.695,0.627,0.577,0.533,0.490,0.439,0.365,0.260,0.090/
     3, VRT/.7,.8,.9,1.05,1.15,1.25/
```

```
      DATA AA/
     A 0.170 , -0.150 , -0.540 , -1.300 , -1.980 , -2.770 ,
     B 0.267 ,  0.010 , -0.300 , -0.860 , -1.330 , -1.925 ,
     C 0.335 ,  0.125 , -0.145 , -0.605 , -0.965 , -1.415 ,
     D 0.378 ,  0.175 , -0.055 , -0.470 , -0.775 , -1.120 ,
     E 0.403 ,  0.212 , -0.005 , -0.383 , -0.665 , -0.975 /
      DATA AB/
     A 0.413 ,  0.233 ,  0.026 , -0.333 , -0.510 , -0.887 ,
     B 0.417 ,  0.245 ,  0.053 , -0.302 , -0.506 , -0.832 ,
     C 0.419 ,  0.254 ,  0.071 , -0.278 , -0.502 , -0.790 ,
     D 0.420 ,  0.262 ,  0.082 , -0.259 , -0.499 , -0.752 ,
     E 0.421 ,  0.271 ,  0.090 , -0.241 , -0.480 , -0.720 /
      DATA AC/
     A 0.000 , -0.360 , -0.800 , -1.570 , -2.430 , -3.900 ,
     B 0.157 , -0.125 , -0.475 , -1.118 , -1.680 , -2.750 ,
     C 0.260 ,  0.018 , -0.258 , -0.788 , -1.075 , -1.670 ,
     D 0.328 ,  0.102 , -0.130 , -0.583 , -0.930 , -1.250 ,
     E 0.365 ,  0.160 , -0.060 , -0.464 , -0.770 , -1.020 /
      DATA AD/
     A 0.386 ,  0.196 , -0.018 , -0.385 , -0.664 , -0.902 ,
     B 0.398 ,  0.220 ,  0.011 , -0.330 , -0.595 , -0.836 ,
     C 0.407 ,  0.238 ,  0.034 , -0.287 , -0.545 , -0.780 ,
     D 0.414 ,  0.252 ,  0.055 , -0.258 , -0.507 , -0.766 ,
     E 0.417 ,  0.263 ,  0.071 , -0.222 , -0.482 , -0.742 /
      DATA AE/
     A -0.215 , -0.590 , -1.140 , -2.150 , -3.150 , -4.450 ,
     B 0.020 , -0.295 , -0.700 , -1.465 , -2.185 , -3.240 ,
     C 0.160 , -0.105 , -0.408 , -0.980 , -1.450 , -2.000 ,
     D 0.255 ,  0.010 , -0.255 , -0.710 , -1.070 , -1.455 ,
     E 0.310 ,  0.088 , -0.145 , -0.554 , -0.860 , -1.180 /
      DATA AF/
     A 0.345 ,  0.152 , -0.075 , -0.450 , -0.725 , -1.024 ,
     B 0.367 ,  0.200 , -0.030 , -0.383 , -0.643 , -0.930 ,
     C 0.386 ,  0.225 ,  0.012 , -0.328 , -0.589 , -0.880 ,
     D 0.401 ,  0.243 ,  0.048 , -0.280 , -0.541 , -0.850 ,
     E 0.412 ,  0.258 ,  0.060 , -0.245 , -0.509 , -0.820 /
```

```
      DATA AG/
     A -0.550   , -0.950   , -1.600   , -2.940   , -3.500   , -5.200   ,
     B -0.250   , -0.570   , -1.020   , -1.900   , -2.650   , -3.920   ,
     C  0.000   , -0.275   , -0.600   , -1.230   , -1.770   , -2.385   ,
     D  0.150   , -0.045   , -0.340   , -0.950   , -1.365   , -1.960   ,
     E  0.255   ,  0.020   , -0.200   , -0.800   , -1.215   , -1.800   /
      DATA AH/
     A  0.315   ,  0.120   , -0.110   , -0.685   , -1.130   , -1.715   ,
     B  0.355   ,  0.173   , -0.050   , -0.614   , -1.087   , -1.665   ,
     C  0.375   ,  0.195   ,  0.000   , -0.575   , -1.060   , -1.640   ,
     D  0.392   ,  0.225   ,  0.032   , -0.545   , -1.035   , -1.625   ,
     E  0.405   ,  0.248   ,  0.060   , -0.520   , -1.017   , -1.617   /
      DATA BA/
     A -0.485   , -0.460   , -0.450   , -0.410   , -0.400   , -0.385   ,
     B -0.335   , -0.330   , -0.315   , -0.300   , -0.295   , -0.280   ,
     C -0.240   , -0.239   , -0.230   , -0.225   , -0.220   , -0.215   ,
     D -0.175   , -0.185   , -0.170   , -0.170   , -0.165   , -0.164   ,
     E -0.140   , -0.145   , -0.135   , -0.140   , -0.135   , -0.135   /
      DATA BB/
     A -0.115   , -0.120   , -0.110   , -0.115   , -0.110   , -0.115   ,
     B -0.100   , -0.105   , -0.100   , -0.100   , -0.100   , -0.100   ,
     C -0.093   , -0.095   , -0.095   , -0.095   , -0.092   , -0.095   ,
     D -0.090   , -0.090   , -0.090   , -0.090   , -0.090   , -0.090   ,
     E -0.088   , -0.088   , -0.088   , -0.088   , -0.088   , -0.085   /
      DATA BC/
     A -0.540   , -0.500   , -0.490   , -0.460   , -0.410   , -0.435   ,
     B -0.365   , -0.350   , -0.335   , -0.320   , -0.305   , -0.305   ,
     C -0.270   , -0.265   , -0.245   , -0.235   , -0.230   , -0.230   ,
     D -0.205   , -0.205   , -0.185   , -0.175   , -0.175   , -0.180   ,
     E -0.165   , -0.160   , -0.145   , -0.140   , -0.140   , -0.145   /
      DATA BD/
     A -0.140   , -0.130   , -0.120   , -0.115   , -0.115   , -0.120   ,
     B -0.125   , -0.110   , -0.105   , -0.100   , -0.100   , -0.105   ,
     C -0.115   , -0.095   , -0.095   , -0.095   , -0.092   , -0.095   ,
     D -0.110   , -0.090   , -0.090   , -0.090   , -0.090   , -0.090   ,
     E -0.105   , -0.085   , -0.085   , -0.085   , -0.088   , -0.085   /
```

```
      DATA BE/
     A -0.595   , -0.535   , -0.535   , -0.460   , -0.445   , -0.445   ,
     B -0.420   , -0.390   , -0.370   , -0.350   , -0.335   , -0.330   ,
     C -0.330   , -0.310   , -0.275   , -0.260   , -0.260   , -0.260   ,
     D -0.275   , -0.265   , -0.215   , -0.205   , -0.205   , -0.195   ,
     E -0.250   , -0.230   , -0.175   , -0.165   , -0.165   , -0.160   /
      DATA BF/
     A -0.235   , -0.205   , -0.145   , -0.145   , -0.140   , -0.138   ,
     B -0.235   , -0.185   , -0.135   , -0.130   , -0.125   , -0.125   ,
     C -0.240   , -0.170   , -0.125   , -0.120   , -0.118   , -0.118   ,
     D -0.250   , -0.155   , -0.120   , -0.115   , -0.115   , -0.113   ,
     E -0.265   , -0.145   , -0.118   , -0.112   , -0.114   , -0.110   /
      DATA BG/
     A -0.670   , -0.610   , -0.570   , -0.525   , -0.475   , -0.480   ,
     B -0.485   , -0.460   , -0.415   , -0.380   , -0.365   , -0.360   ,
     C -0.395   , -0.373   , -0.335   , -0.293   , -0.285   , -0.280   ,
     D -0.348   , -0.322   , -0.285   , -0.235   , -0.232   , -0.225   ,
     E -0.331   , -0.300   , -0.255   , -0.200   , -0.195   , -0.190   /
      DATA BH/
     A -0.337   , -0.295   , -0.238   , -0.176   , -0.171   , -0.168   ,
     B -0.360   , -0.300   , -0.231   , -0.163   , -0.157   , -0.154   ,
     C -0.400   , -0.310   , -0.230   , -0.157   , -0.150   , -0.145   ,
     D -0.447   , -0.323   , -0.229   , -0.155   , -0.146   , -0.139   ,
     E -0.499   , -0.336   , -0.230   , -0.153   , -0.144   , -0.135   /
      FRICT(RE)=(.86859*ALOG(RE/(1.964*ALOG(RE)-3.8215)))**(-2)
C
C       ZK   IS THE DECIMAL PART OF THE ANNULUS OCCUPIED BY THE
C       AUXILIARY INLET THAT IS ACTUALLY OPENING.  THE REMAINDER IS
C       STRUCTURE.
C
      ZK=.8
      SPO=(HS+HA)*RHOW*G
      PVP=PV*RHOW*G
      VELR(1)=VI(1)/VO(1)
C
C       SIGTV  IS THE INCIPIENT CAVITATION NO. ON THE ELBOW TURNING
```

```
C     VANES REFERENCED TO DIFFUSER EXIT PRESSURE AND VELOCITY.
C
      SIGTV=0.4
      JNUMB=2
C
C     NUMB  IS AN INDEX INDICATING THE TOTAL NO. OF SPEEDS TO BE
C     EXAMINED.
C        NUMB=2 IF ONLY CRUISE AND TAKE-OFF ARE SPECIFIED.
C        NUMB=3 OR MORE IF ONE OR MORE OFF-DESIGN SPEEDS ARE SPECIFIED.
C
C     ISTRT  IS AN INDEX INDICATING WHETHER THE CURRENT OPERATION IS
C     PART OF THE DESIGN PROCESS, IN WHICH ITS VALUE IS 1, OR PART OF
C     THE EVALUATION PROCESS, IN WHICH CASE ITS VALUE IS 3 .
C
      IF(ISTRT.EQ.3)JNUMB=NUMB
      DO 10 I=ISTRT,JNUMB
      QO(I)=.5*RHOW*VO(I)*VO(I)
C
C     SIGI(I) IS THE INCIPIENT CAVITATION NO. REFERENCED TO FREE STREAM
C     CONDITIONS.
C
      SIGI(I)=(SPO-PVP)/QO(I)
      PTO(I)=SPO+QO(I)
   10 CONTINUE
      IF(TRIM(1).GT.3.)TRIM(1)=3.
      CPEX=-SIGI(1)
C
C     INTERPOLATE IN THE DATA TABLE TO FIND THE INLET WITH THE DESIRED
C     PRESSURE COEFFICIENT.
C
      DO 610 I=1,2
      DO 609 K=1,10
      DO 608 J=1,6
      CDUMX(J)=CPEXT(J,K,I)
  608 CONTINUE
      CDUMY(K)=TABLE(VRT,CDUMX,VELR(1),NL)
```

```
  609 CONTINUE
      XDTT(I)=TABLE(CDUMY,XDT,CPEX,KL)
  610 CONTINUE
      ML(1)=2
      XD=TABLE(AT,XDTT,TRIM(1),ML)
      DIDM=TABLE(XDT,DIDMT,XD,KL)
C
C       IF THE TRIAL NACELLE HAS LESS FRONTAL AREA THAN THE MINIMUM
C       REQUIRED TO AVOID CAVITATION, REJECT THE TRIAL VALUE.  IF NON-
C       CAVITATING, CALCULATE INLET DIMENSIONS.
C
      QI=.5*Q(1)
      AI=QI/VI(1)
      DI=SQRT(AI)*1.12838
      DM=DI/DIDM
   11 CONTINUE
      ELEXT=DM*XD
      CPIN=-SIGI(2)
C
C       INTERPOLATE IN THE DATA TABLE TO DETERMINE THE MAXIMIM VELOCITY
C       RATIOS AT CRUISE AND TAKE-OFF.
C
      DO 710 I=1,4
      DO 709 K=1,6
      DO 708 J=1,10
      CDUMX(J)=CPINT(K,J,I)
  708 CONTINUE
      CDUMY(K)=TABLE(XDT,CDUMX,XD,KL)
  709 CONTINUE
      VRTT(I)=TABLE(CDUMY,VRT,CPIN,IL)
      VRTEX(I)=TABLE(CDUMY,VRT,CPEX,IL)
  710 CONTINUE
      ML(1)=4
      VRMAX(1)=TABLE(ALFAT,VRTEX,TRIM(1),ML)
      VRMAX(2)=TABLE(ALFAT,VRTT,TRIM(2),ML)
C
```

```
C      CHECK FOR LIP CAVITATION AT CRUISE.  IF CAVITATING, REJECT.
C
      IF(VELR(1).GT.VRMAX(1).AND.DELTA.GT.1.E-9)RETURN
C
C      DETERMINE MAX. FLOW RATE AT TAKE-OFF AND COMPARE WITH REQUIRED
C      FLOW RATE.  AN AUXILIARY INLET MUST BE SIZED TO ACCEPT ANY EXCESS
C      REQUIRED FLOW.
C
      QIN=AI*VRMAX(2)*VO(2)
C
C     ASSUMING THE AUX. INLETS ALLOW FLOW TO ENTER BEFORE THE DIFFUSER,
C     CALCULATE LOSSES AND TOTAL PRESSURE OF THE COMBINED FLOW.
C
      QC=0.5*Q(2)
      QAUX=QC-QIN
      IF(QAUX.LE.0.)QAUX=0.
      QIN=QC-QAUX
      KDEX=0
C     CALCULATE STATIC PRESSURE IMMEDIATELY AFT. OF THE LIP.
      VI2=QIN/AI
      VR=VI2/VO(2)
      PRL2=TABLE(VRT,PRLT,VR,JL)
      PTI=PRL2*QO(2)+SPO
      SPI=PTI-0.5*RHOW*VI2*VI2
C     CALCULATE COMBINED FLOW PRESSURES AND AUX. INLET AREA.
      AIAUX=0.
      VIAUX=0.
      PTAUX=0.
      IF(QAUX.EQ.0.)GO TO 12
      PRAUX=0.80
      PTAUX=PRAUX*QO(2)+SPO
      DYP=PTAUX-SPI
      VIAUX=SQRT(2.*DYP/RHOW)
      AIAUX=QAUX/VIAUX
C
C      THE TOTAL PRESSURE OF THE COMBINED FLOW IS CALCULATED AS THE
```

```
C       MASS WEIGHTED AVERAGE OF THE COMBINING FLOWS.
C
   12 CONTINUE
      PC=(PTI*QIN+PTAUX*QAUX)/QC
      VI(2)=SQRT(2.*(PC-SPI)/RHOW)
      DLIP(2)=1.-(PC-SPO)/QO(2)
      QDIF=QC
C
C       CALCULATE THE INTERNAL LENGTHS TO THE DIFFUSER ENTRY.
C
      ELENT=ELEXT/9.
      PHI=ATAN(.5*(DM-DI)/ELEXT)
      PHS=SIN(PHI)
      X=.5*(SQRT(DI**2+1.27324*AIAUX*PHS/ZK)-DI)/PHS
      ELAUX=X/COS(PHI)
C     SIZE THE DIFFUSER
      D2=0.9*DM
      D1=DI
      IF(D2.LT.D1)D2=D1
      ELMAX=9.22339*(D2-D1)
      ELMIN=2.836075*(D2-D1)
C
C     DECIDE WHICH CONDITION GOVERNS THE DIFFUSER.
C
      IF(QI.GT.QC)GO TO 13
      II=2
      GO TO 14
   13 CONTINUE
      II=1
      QDIF=QI
   14 CONTINUE
      EL=0.5*(ELMAX+ELMIN)
      DEL=0.
  111 EL=EL+DEL
      KDEX=KDEX+1
      IF(KDEX.GT.10)GO TO 112
```

```
      ELD=ELENT+EL+3.54491*D2+ELAUX
      ELL=5.5*DM
      ELN=ELD
      IF(ELL.GE.ELD)ELN=ELL
      ELFAC=(ELD-ELL)
      DDM=0.5*(D2+D1)
      XKT=(1.-(D1/D2)**2)**2
      IF(ELFAC.LE.0.)ELFAC=0.
      REL=VO(II)*ELN/GNU
      RED=VI(II)*D1/GNU
      DL=DM/ELN
      CDRG =CFS(REL)*(1.+1.5*DL**(3/2)+7.*DL**3)
      ANGL=0.
      IF(EL.LT.0.001)GO TO 109
      ANGL=ATAN((D2-D1)/(2.*EL    ))*57.2958
  109 CDIF=3.19E-3*ANGL*ANGL+8.452E-4*ANGL
      POW=CDRG*DM*.5*PI*RHOW*VO(II)**3*ELFAC+(CDIF*XKT+FRICT(RED)*EL/DDM
     1)*.5*RHOW*VI(II)*VI(II)*QDIF
      DEL=.1*(ELMAX-ELMIN)
      IF(KDEX.EQ.1)GO TO 110
      DEL=(POWI-POW)*EL/POWI
  110 POWI=POW
      IF(DEL.LE.0.01*EL)GO TO 112
      GO TO 111
C
C      ELDIF  IS THE DIFFUSER LENGTH REQUIRING THE LEAST TOTAL POWER
C      FOR THE DESIRED  DIFFUSION RATIO.
C
  112 ELDIF=EL
C
C      CALCULATE THE LIP LOSSES FOR EACH SITUATION.
C
      DLIP(1)=1.-TABLE(VRT ,PRLT,VELR(1),JL)
      IF(NUMB.LT.3)GO TO 113
      DO 15 J=3,NUMB
      VI(J)=.5*Q(J)/AI
```

```
      VELR(J)=VI(J)/VO(J)
      DLIP(J)=1.-TABLE(VRT,PRLT,VELR(J),JL)
   15 CONTINUE
  113 JNUMB=2
      IF(ISTRT.EQ.3)JNUMB=NUMB
      DO 17 I=ISTRT,JNUMB
      CAV(I,3)=0.
C
C      CALCULATE THE DIFFUSER AND PIPE LOSSES FOR EACH SITUATION AND
C      ADD TO THE LIP LOSSES.
C
      REND=D1*VI(I)/GNU
      DDIF=(CDIF*XKT+FRICT(REND)*ELDIF/DDM)*0.5*RHOW*VI(I)*VI(I)
      PLOSS=DLIP(I)*QO(I)+DDIF+FRICT(REND)*ELAUX/DI*.5*RHOW*VI(1)*VI(1)
      IF(I.EQ.2)PLOSS=DLIP(2)*QO(2)+DDIF
      VAOUT=O(I)*0.63662/(D2*D2)
      SQUAR=SIGI(I)+1.-PLOSS/QO(I)
C
C      DETERMINE THE CRITICAL LOCAL VELOCITY AT THE DIFFUSER EXIT AT
C      WHICH CAVITATION ON THE TURNING VANES OCCURS.
C
      VCRIT=SQRT(SQUAR)*VO(I)/SQRT(1.+SIGTV)
C
C      ESTIMATE THE MAXIMUM LOCAL VELOCITY AT THE DIFFUSER EXIT.
C
      VMAX=1.50*VAOUT
C
C      IF CAVITATION OCCURS, REJECT ON DESIGN, INDICATE ON EVALUATION.
C
      IF(VMAX.GT.VCRIT.AND.ISTRT.EQ.1.AND.DELTA.GT.1.E-9)GO TO 16
      IF(VMAX.GT.VCRIT)CAV(I,3)=1.
      GO TO 17
   16 CONTINUE
      DM=1.05*DM*SQRT(VMAX/VCRIT)
      DIDM=DI/DM
      XD=TABLE(DIDMT,XDT,DIDM,KL)
```

```
      GO TO 11
C     AT THIS POINT THE DIFFUSER HAS BEEN SIZED TO AVOID CAVITATION AT
C      BOTH TAKE/OFF AND CRUISE. INTERNAL FLOW LOSSES ARE DETERMINED
C
      DELH(I,1)=PLOSS/(RHOW*G)
C      THE FOLLOWING CARD IS USED ONLY WITH A TEST PROGRAM.
      PRC(I)=(PTC(I)-PLOSS-SPO)/QO(I)
C
C      CALCULATE THE DRAG COEFFICIENTS.
C
      RENL=ELN*VC(I)/GNU
      CD(I)=CFS(RENL)*(1.+1.5*(DM/ELN)**(3/2)+7.*(DM/ELN)**3)
C
C     CALCULATE WETTED SURFACE AND DRAG.
C
      EM=SQRT(1.+4.*((2.*ELEXT)/DM)**2)
      AEXN=1.0472*DM*DM*(EM+1./(EM+1.))
      AEXN=AEXN+PI*DM*(ELN-2.*ELEXT)
      CPOD(I)=2.*QO(I)*AEXN*CD(I)
   17 CONTINUE
      AREA(1)=PI*D2*D2*0.5
      CGS(1,1)=HS+HE-HCL
      CGS(2,1)=XLS+.5*(ELN-3.54491*D2)
      IF(THATA(1).GE.90.)GO TO 18
      PHI=THATA(1)/57.2958
      CGS(2,1)=CGS(2,1)+CGS(1,1)/TAN(PHI)
   18 CGS(3,1)=0.
      CGS(4,1)=0.
      WGTS(1,1)=.11*DM*AEXN*(.5*RHOD-RHOW)+15.07*AREA(1)*(ELENT+ELAUX+EL
     1)
      RETURN
      END
```

CHART TITLE - SUBROUTINE NACEL

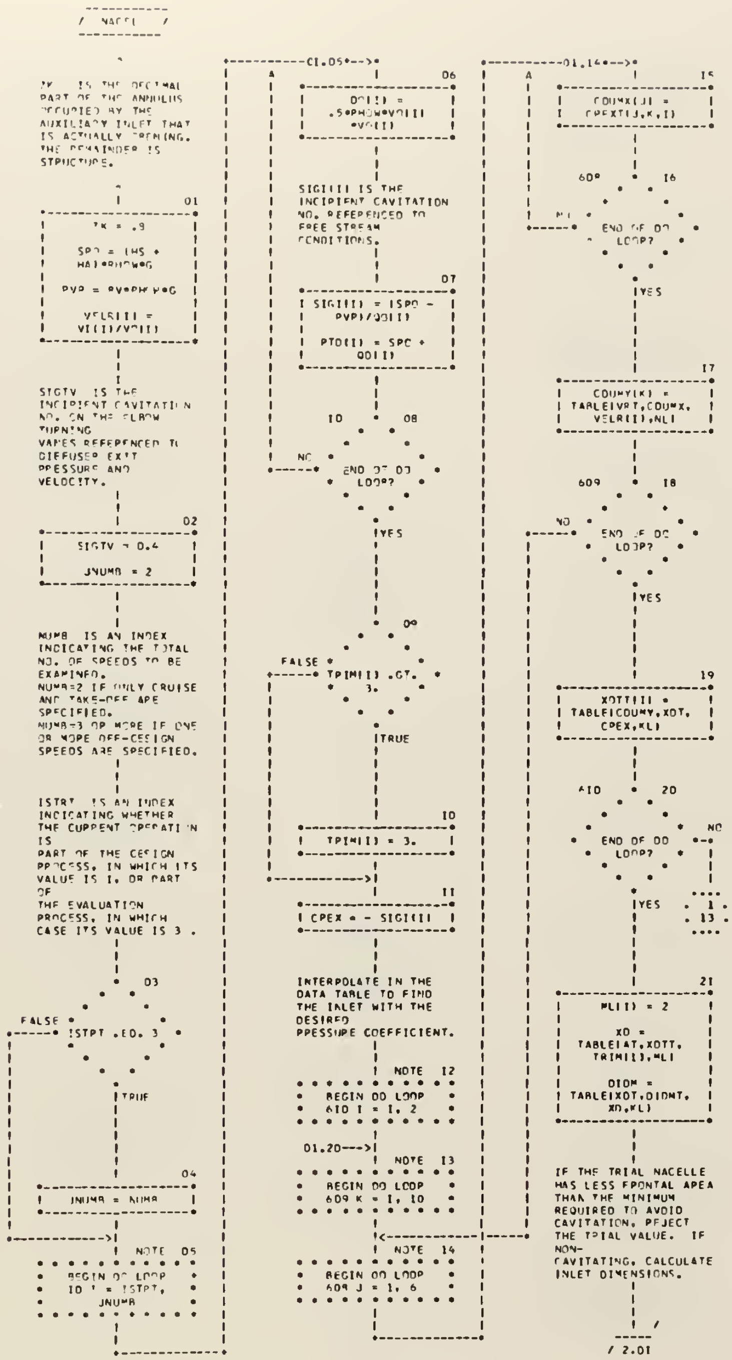
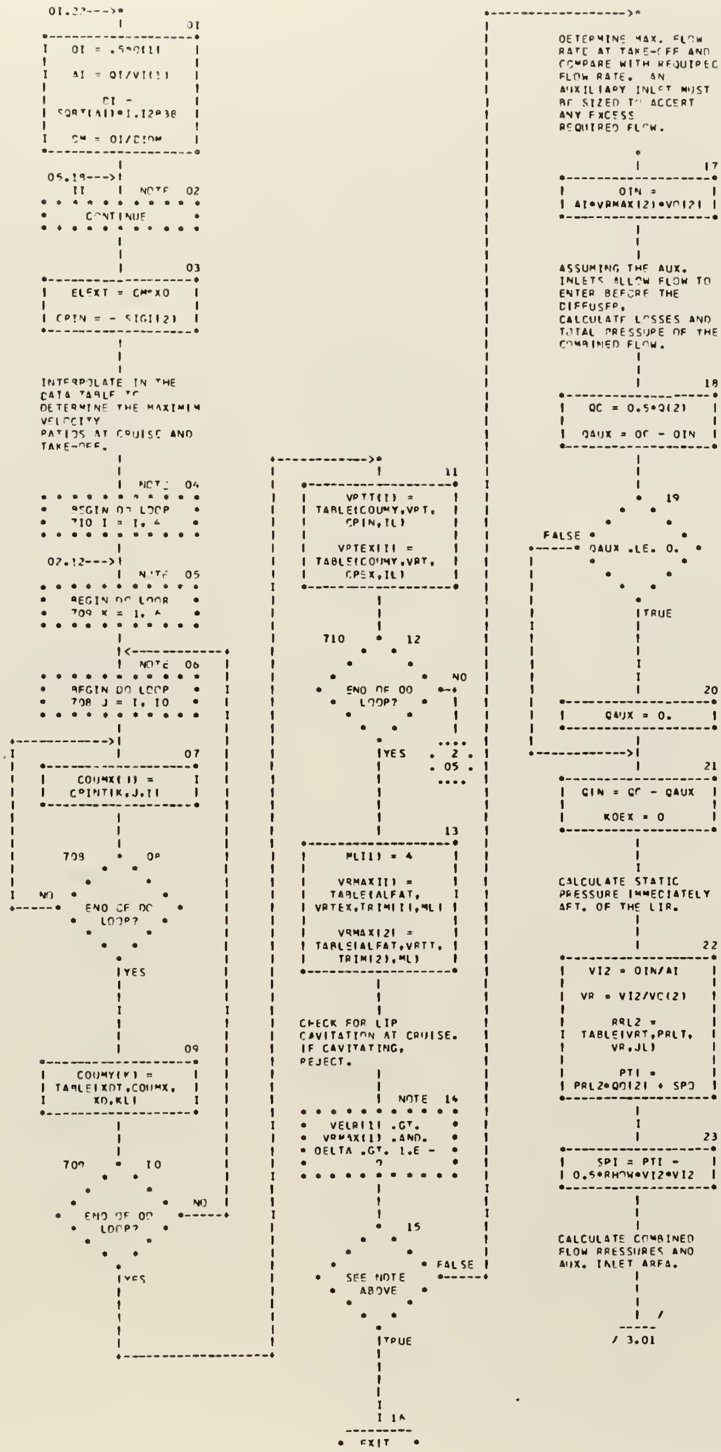


CHART TITLE - SUBROUTINE NACEL



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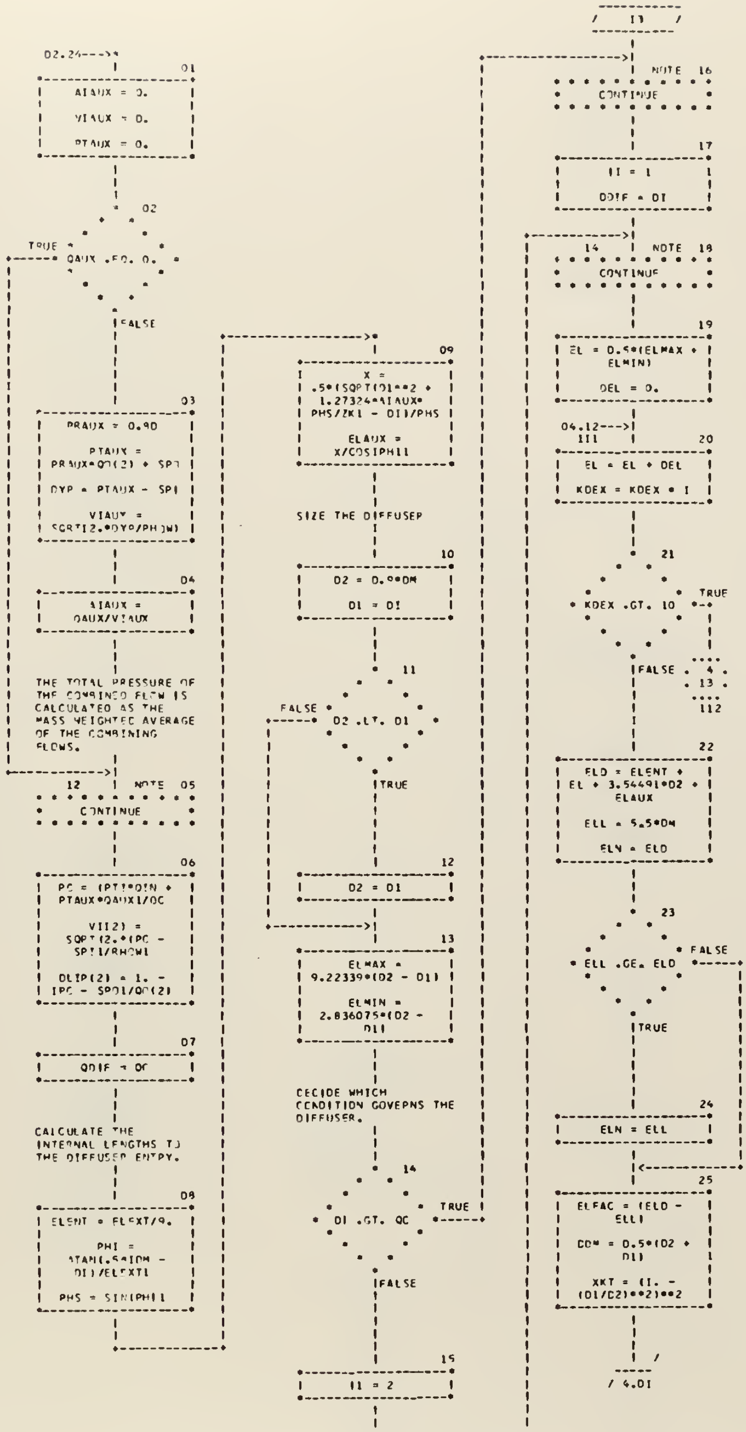

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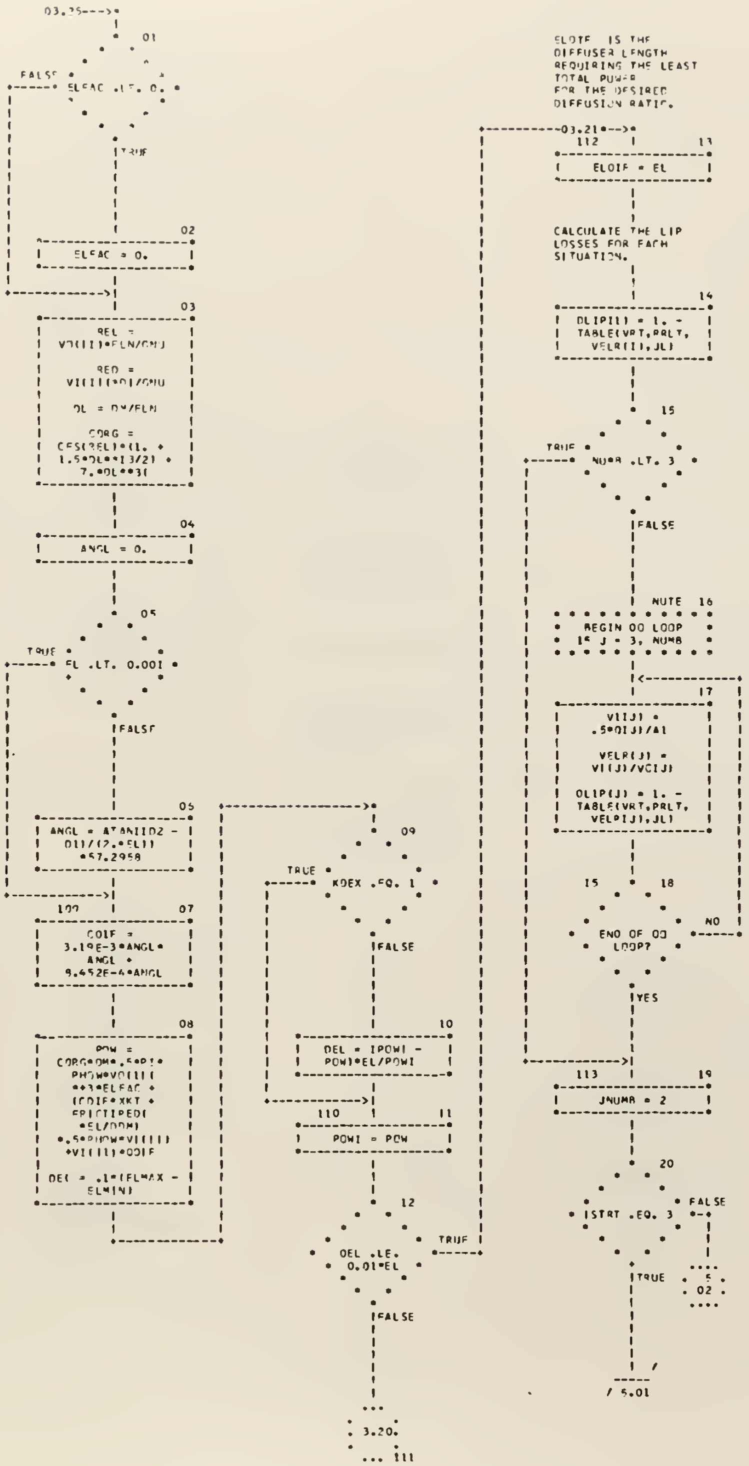

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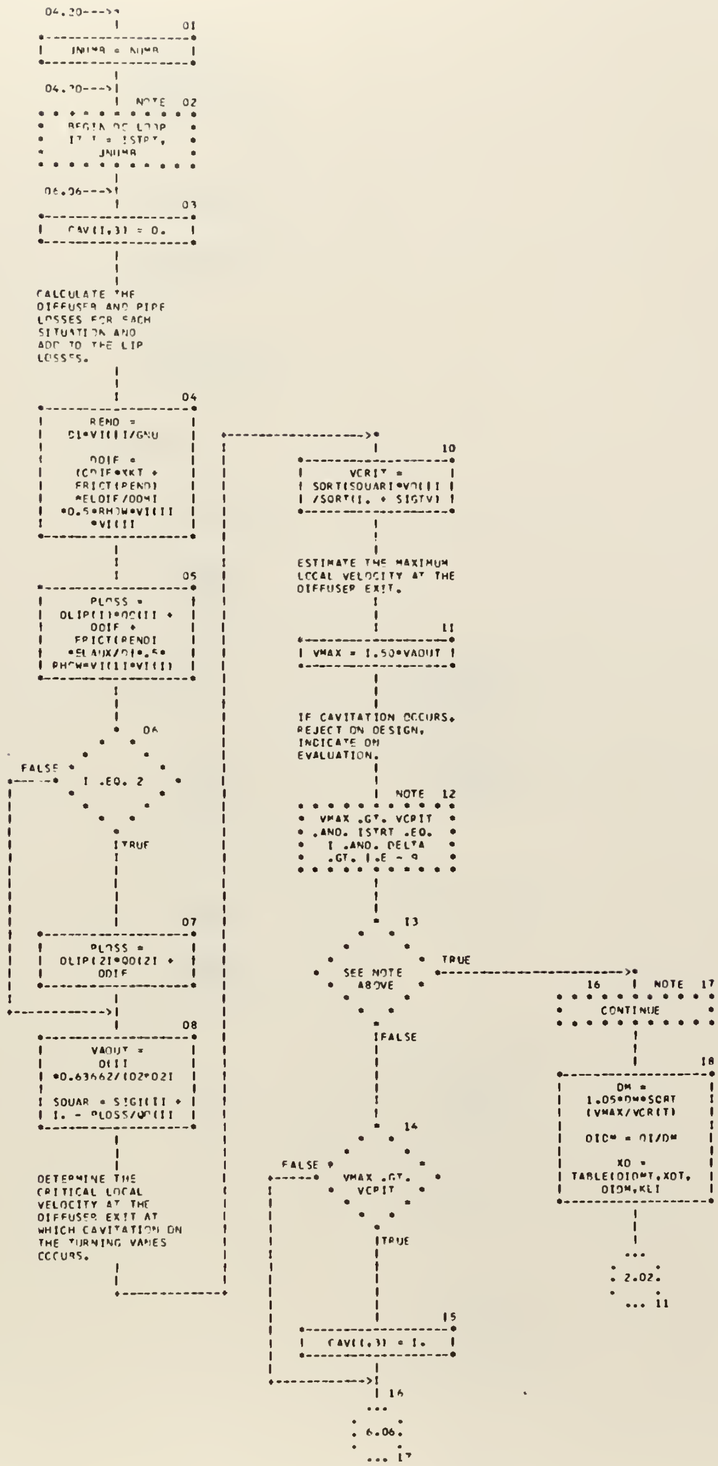

```
 AT THIS POINT THE
 DIFFUSER HAS BEEN
 SIZED TO AVOID
 CAVITATION AT
 BOTH TAKE/OFF AND
 CRUISE. INTERNAL FLOW
 LOSSES ARE DETERMINED

            *
            I          01
 *---------------------*
 I    DELH(I,1) =      I
 I  PLOSS/(RHOW*G)     I
 *---------------------*
            I
            I
            I
 THE FOLLOWING CARD IS
 USED ONLY WITH A TEST
 PROGRAM.
            I
            I
            I          02
 *---------------------*
 I     PRC(I) =        I
 I (PTO(I) - PLOSS -   I
 I    SPD)/QO(I)       I
 *---------------------*
            I
            I
            I
 CALCULATE THE DRAG
 COEFFICIENTS.
            I
            I
            I          03
 *---------------------*
 I      RENL =         I
 I  ELN*VO(I)/GNU      I
 I                     I
 I      CD(I) =        I
 I CFS(RENL)*(1. +     I
 I  1.5*(DM/ELN)       I
 I     **(3/2) +       I
 I 7.*(DM/ELN)**3)     I
 *---------------------*
            I
            I              *----------------------->*
            I              I                        I          07
 CALCULATE WETTED          I            *---------------------*
 SURFACE AND DRAG.         I            I     AREA(I) =       I
            I              I            I   PI*D2*D2*0.5      I
            I              I            I                     I
            I          04  I            I  CGS(1,1) = HS +    I
 *---------------------*   I            I    HE - HCL         I
 I  EM = SQRT(1. +     I   I            I                     I
 I  4.*((2.*ELEXT)     I   I            I CGS(2,1) = XLS +    I
 I     /DM)**2)        I   I            I   .5*(ELN -         I
 I                     I   I            I  3.5449I*D2)        I
 I      AEXN =         I   I            *---------------------*
 I 1.0472*DM*DM*(EM    I   I                        I
 I  + 1./(EM + 1.))    I   I                        I
 *---------------------*   I                        I
            I              I                        *    08
            I              I                      *   *
            I          05  I                    *       *
 *---------------------*   I          TRUE *               *
 I   AEXN = AEXN +     I   I       *------* THATA(I) .GE. *
 I   PI*DM*(ELN -      I   I       I        *    90.      *
 I     2.*ELEXT)       I   I       I          *       *
 I                     I   I       I            *   *
 I     CPDD(I) =       I   I       I              *
 I     2.*DD(I)        I   I       I              IFALSE
 I   *AEXN*CD(I)       I   I       I              I
 *---------------------*   I       I              I
            I              I       I              I
 05.16--->  I              I       I              I
            I              I       I              I
    17      *    06        I       I              I          09
          *   *            I       I  *---------------------*
        *       *          I       I  I       PHI =         I
      *           *    NO  I       I  I THATA(I)/57.2958    I
   *  END OF DO    *--*    I       I  I                     I
      *  LOOP?    *   I    I       I  I     CGS(2,1) =      I
        *       *     I    I       I  I     CGS(2,1) +      I
          *   *       I    I       I  I CGS(1,1)/TAN(PHI)   I
            *        ....  I       I  *---------------------*
            IYES    . 5 .  I       I              I
            I       . 03 . I       *------------->I
            I        ....  I               18     I          10
            I              I          *---------------------*
            I              I          I   CGS(3,1) = 0.     I
            I              I          I                     I
            *--------------*          I   CGS(4,1) = 0.     I
                                      *---------------------*
                                                  I
                                                  I
                                                  I          11
                                      *---------------------*
                                      I    WGTS(1,1) =      I
                                      I .11*DM*AEXN*(.5*    I
                                      I   RHOO - RHOW) +    I
                                      I   15.07*AREA(I)     I
                                      I *(ELENT + ELAUX +   I
                                      I       FL)           I
                                      *---------------------*
                                                  I
                                                  I  12
                                              ---------
                                              *  EXIT  *
                                              ---------
```

Appendix E. ASSUMED CONSTANTS AND LIMITS

It was necessary to make numerous assumptions and impose limits on various quantities in the subroutine. Some of the assumptions were somewhat arbitrary and may be modified whenever good reasons to do so are discovered.

Some of those assumptions and limits are discussed here in the approximate order in which they are encountered in SUBROUTINE NACEL.

The first assumption that should be mentioned is that everything in the model is based on a nacelle with a circular cross section. No attempt was made to account for other shapes.

The decimal constant, ZK, which determines the amount of available inlet area in the auxiliary inlet ring has an arbitrary value of 0.8. The real case may vary widely from this depending on the details of the design.

The incipient cavitation number on the turning vanes, SIGTV, has a value of 0.4. This value was accepted as a reasonable one for the speed range of interest. No examples with which to compare were found in the literature.

The angle of attack at cruise, TRIM(1), has been artificially limited to a maximum of three degrees because the external pressure coefficients are not single valued with respect to L/D_m or D_i/D_m for $\alpha \geq 4^{\circ}$. The highest tabulated value for angle of attack is 6° and extrapolation would probably not be valid.

The range of tabulated velocity ratios is from 0.7 to 1.25. Extrapolation is allowed in the subroutine but the results could contain large errors if extrapolated very far.

The largest value of L/D_m in the tables is 2.50. This is also allowed to be extrapolated and the same remarks apply as for the velocity ratios.

D_i/D_m is limited to 0.90, which assumes a wall thickness allowance of $0.05D_m$. This value is arbitrary and may be modified as desired.

The pressure loss factor for the auxiliary inlet is assumed to be 0.2 which contains an underlying assumption that its inlet velocity ratio is always near 1.0.

Diffuser lengths are limited to those corresponding to double angles of 6° to 20°. See chapter 4 for an explanation of the limits.

In the wetted surface calculation, the area of fairings into the foils and strut, as well as the missing area in way of the foils and strut are ignored. The nacelle is assumed to be a solid body of revolution.

Interference drag between the nacelle and the other components is assumed to remain constant even though the nacelle size changes. No attempt is made to account for the effect of V_i/V_o or the depth of submergence on drag. Chapter 8 contains recommendations concerning this subject.

The weight estimate, as discussed in chapter 6, is only a rough approximation with a series of assumptions as to the construction and material.